ARPA-E LENR Workshop
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Toward a LENR Reference Experiment

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Questions addressed in this presentation:

A. What kind of diagnostic evidence is needed “that is convincing to the wider scientific community”?

B1. What is the common denominator of different LENR systems?

B2. How does that inform the range of diagnostic evidence available?

C. Implications for future research:
Given the above, how to move forward (two options discussed)?

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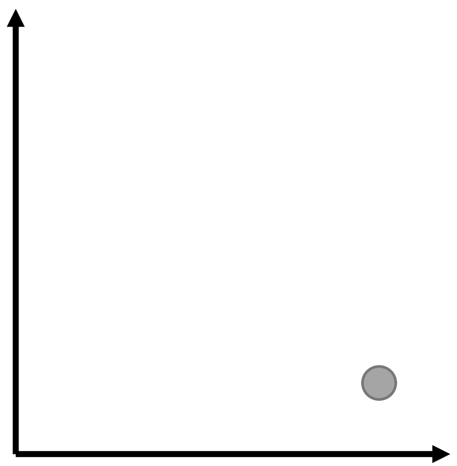
A. What does a convincing LENR reference experiment entail?

The reproducibility challenge and the ambiguity challenge



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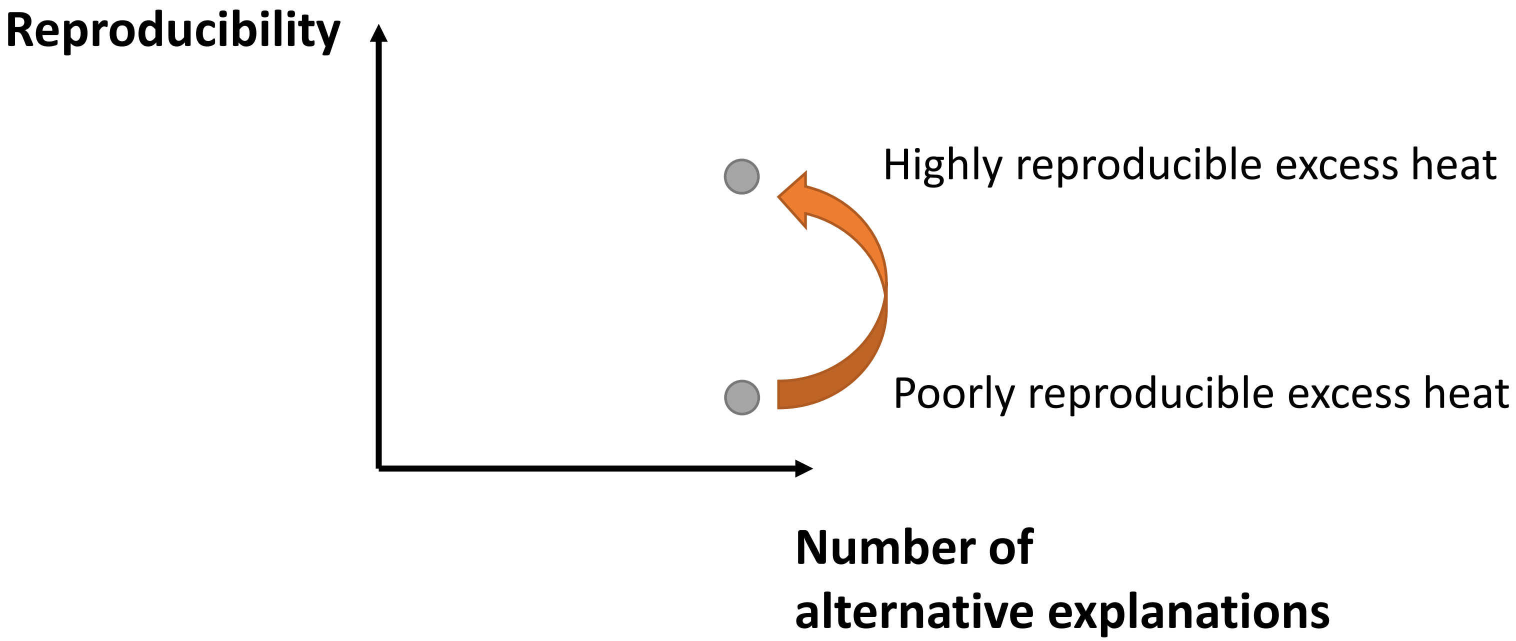

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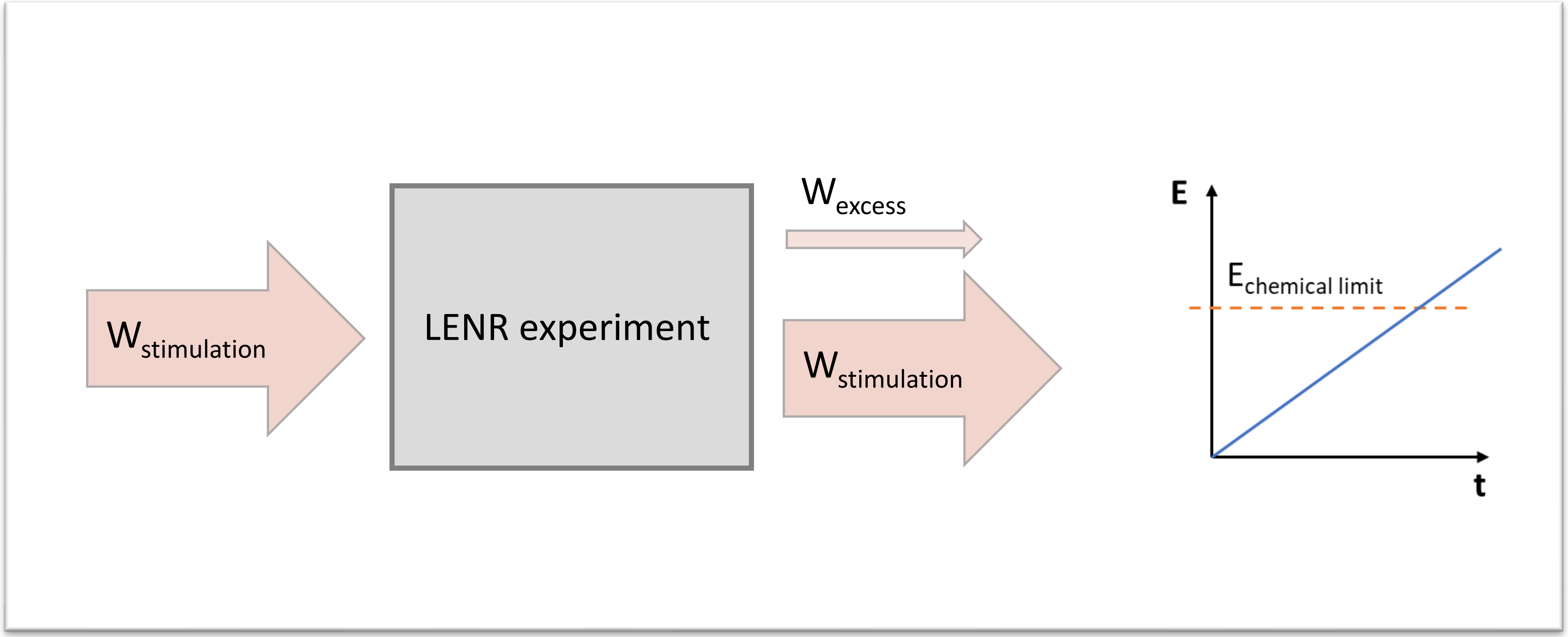
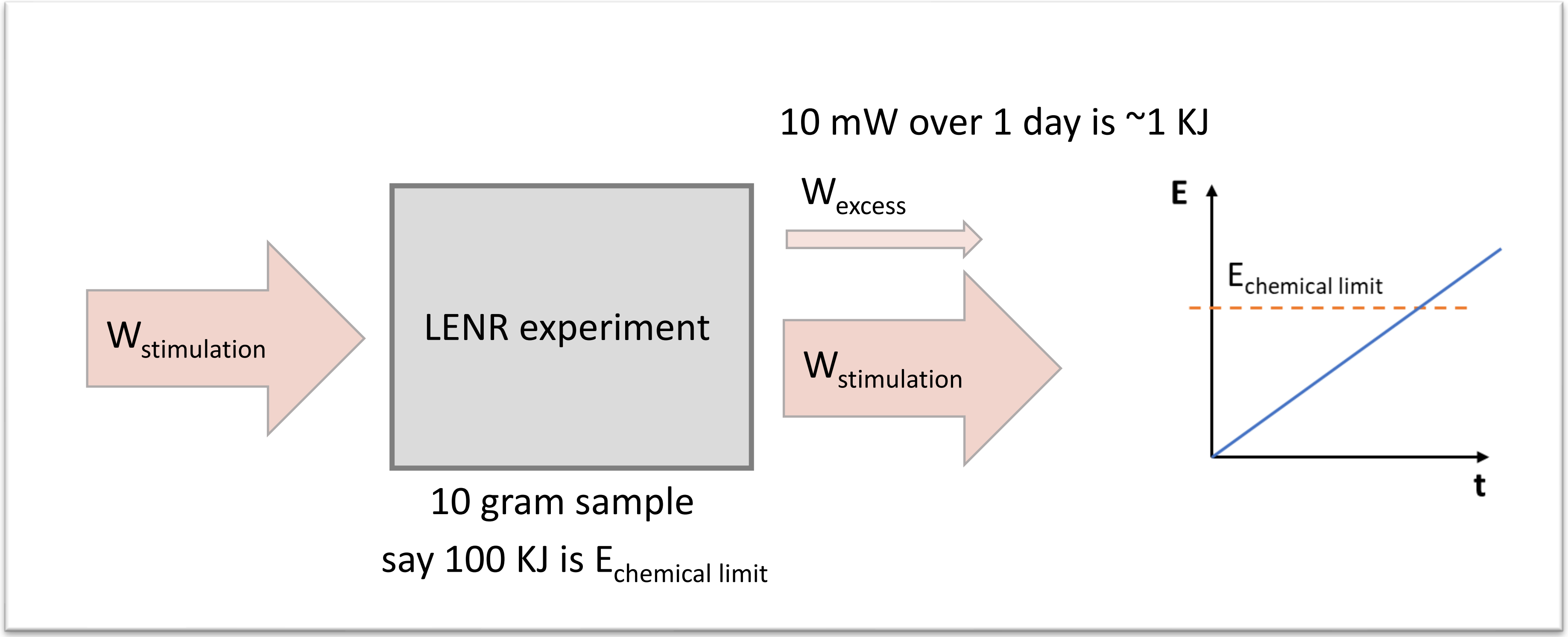


Number of alternative explanations

Toward a LENR reference experiment

The reproducibility challenge and the ambiguity challenge



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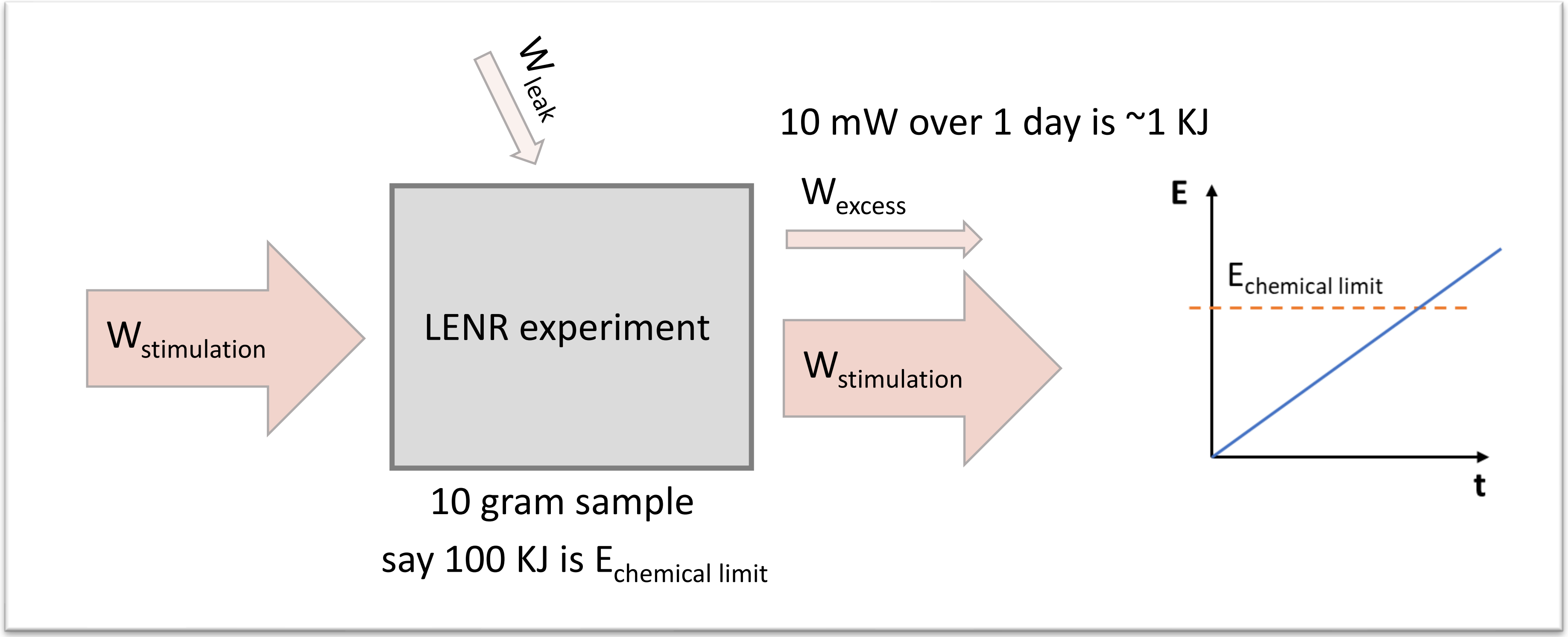

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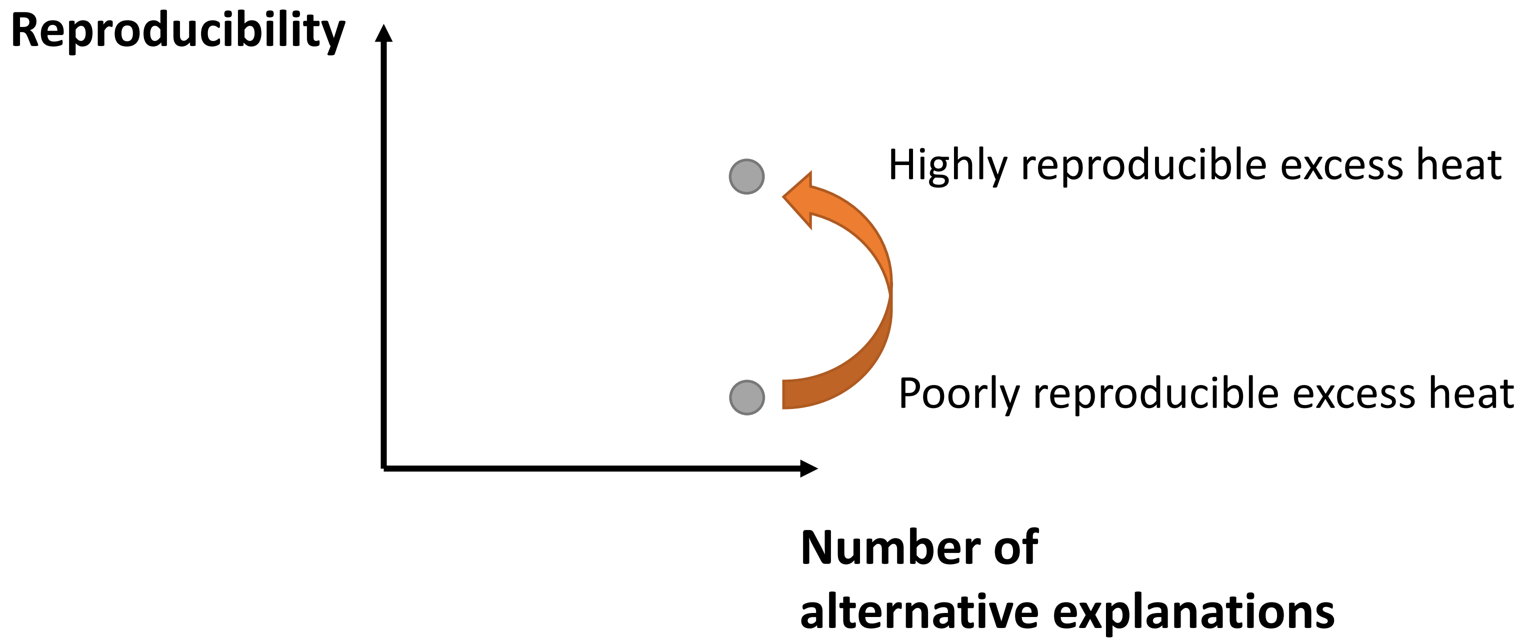

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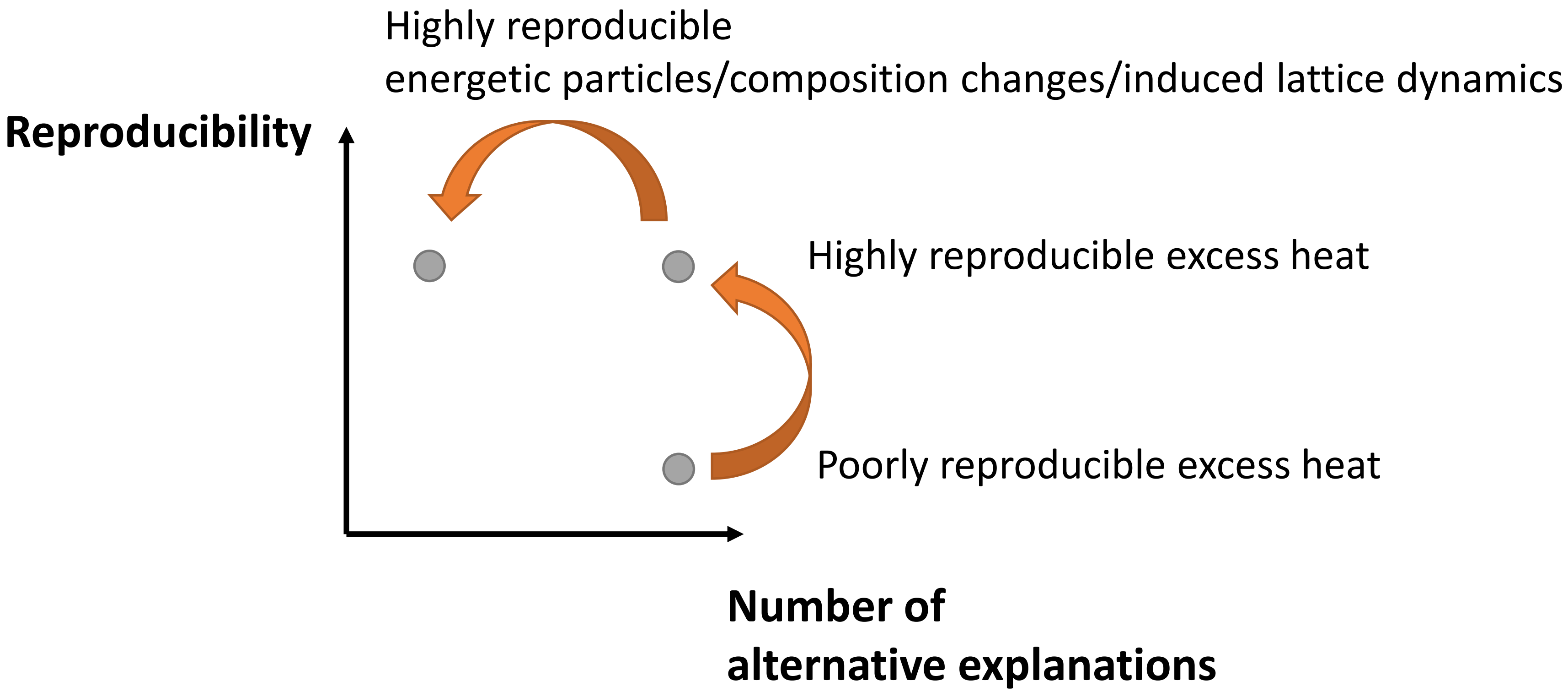

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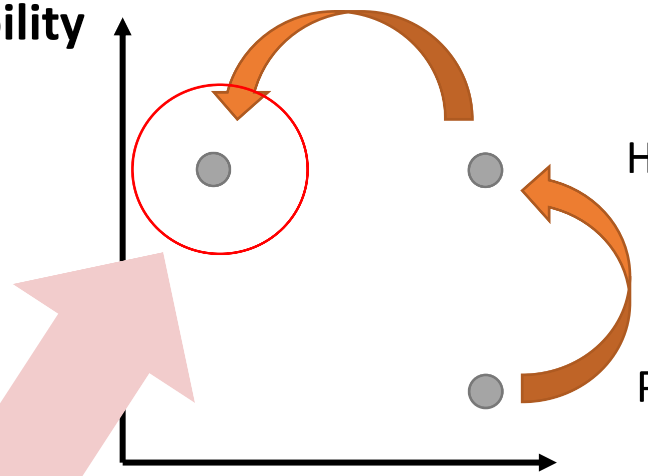
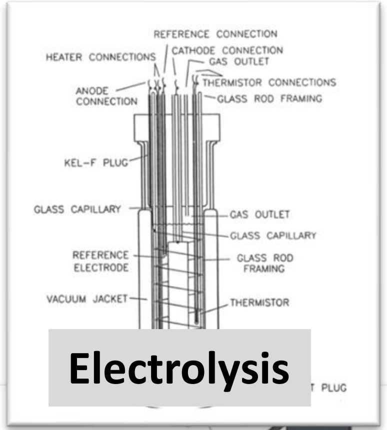
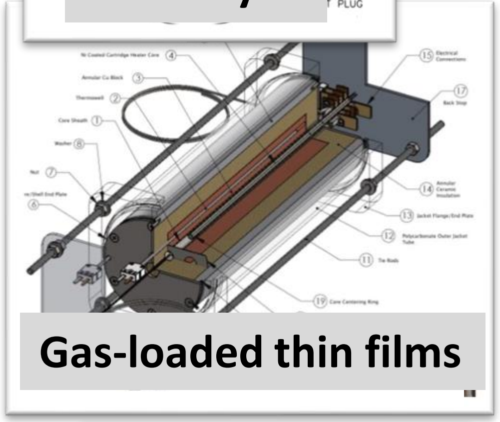
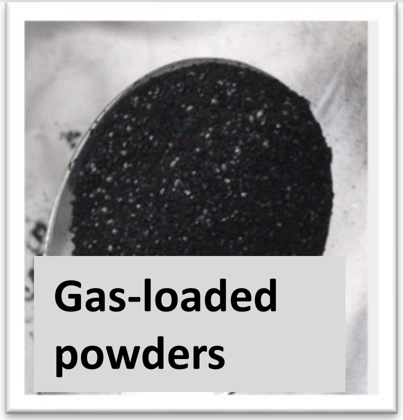


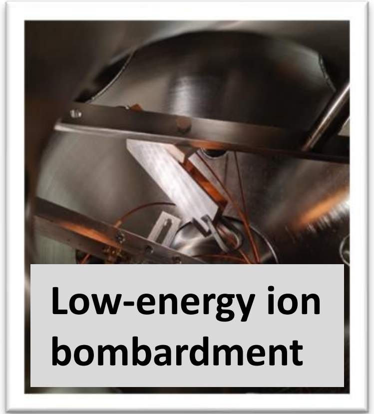
Goal: high producibility, low ambiguity
How to get there?

B1. Taxonomy of LENR experiments and characterization modes





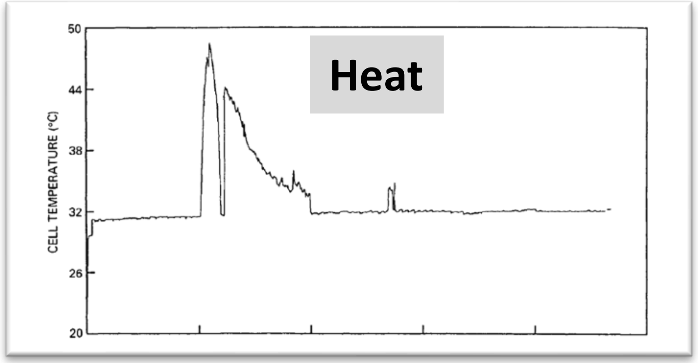


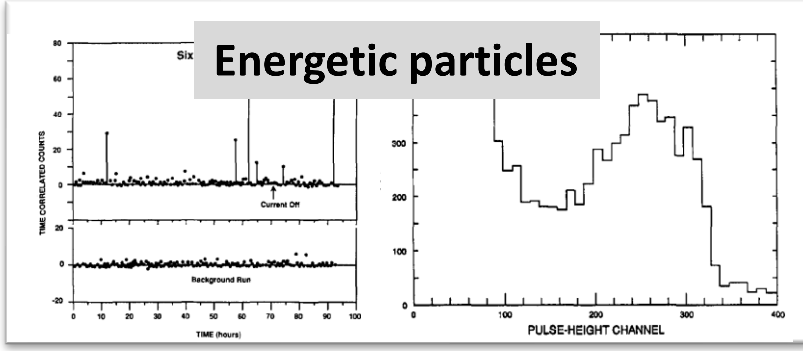


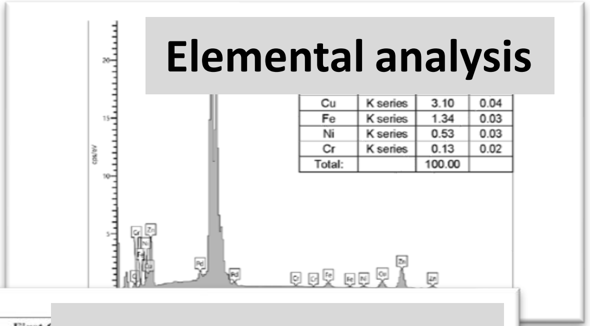
Large variety of experimental configurations

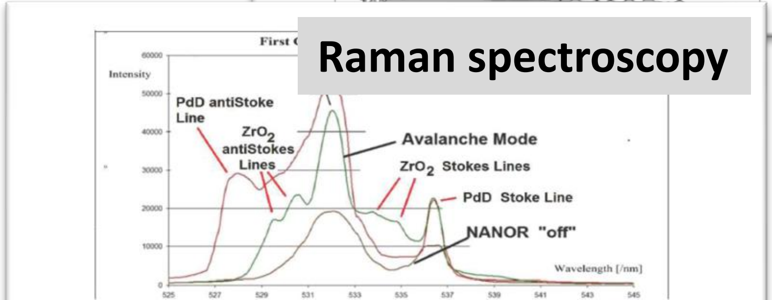
LENR experiments

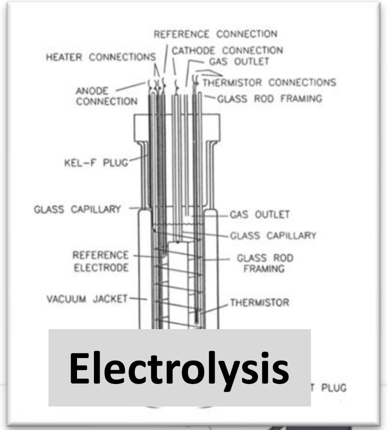
Large variety of characterization modes

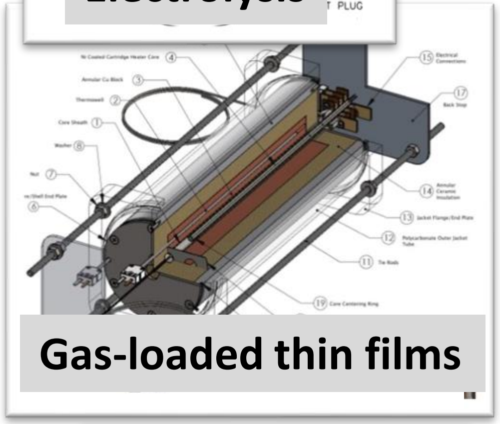


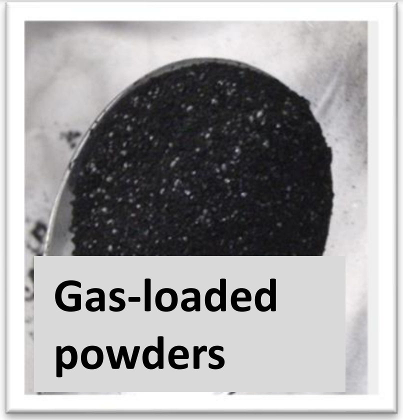


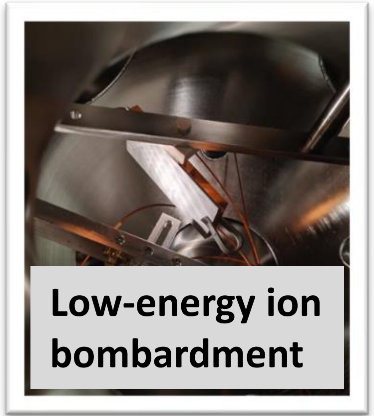












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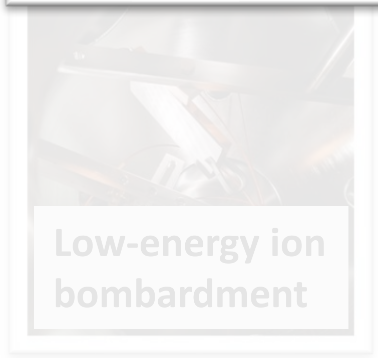


SOLID-STATE STRUCTURE

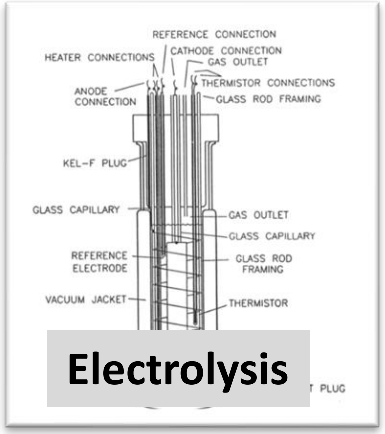
- Bulk (foils)
- Thin films (sputtered or electrodeposited)
- Powders (with embedded nanoparticles)

HYDROGEN LOADING

- Gas pressure
- Electrolysis
- Ion implant

STIMULATION

- Laser
- Hydrogen diffusion
- Ion bombardment
- Electric pulses
- Temperature (300-1000 C)



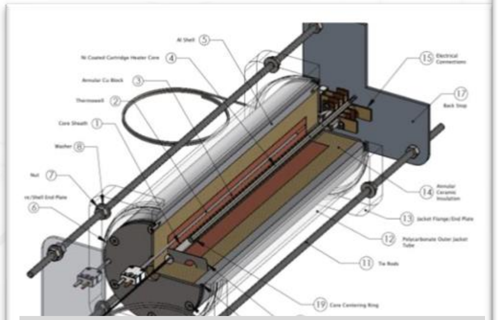
Gas-loaded thin films

Gas-loaded powders

Low-energy ion bombardment

SOLID-STATE STRUCTURE	HYDROGEN LOADING	STIMULATION
Bulk (foils)	Gas pressure	Laser
Thin films (sputtered or electrodeposited)	**Electrolysis**	**Hydrogen diffusion**
Powders (with embedded nanoparticles)	Ion implant	Ion bombardment
		Electric pulses
		Temperature (300-1000 C)

Electrolysis



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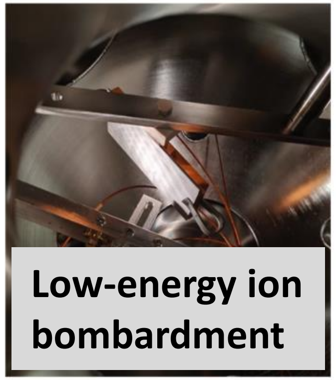

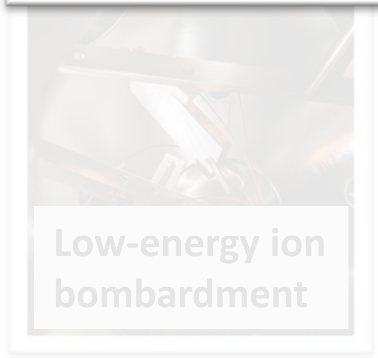

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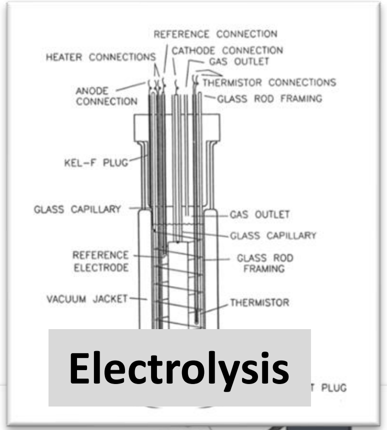
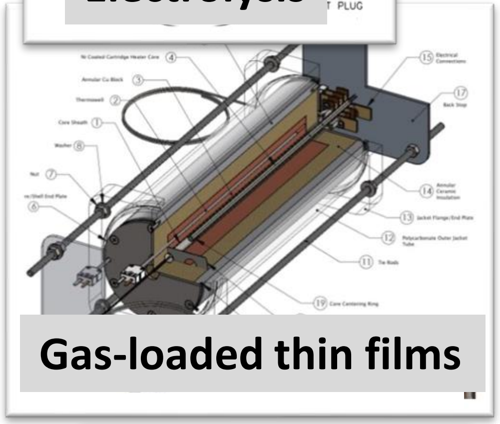
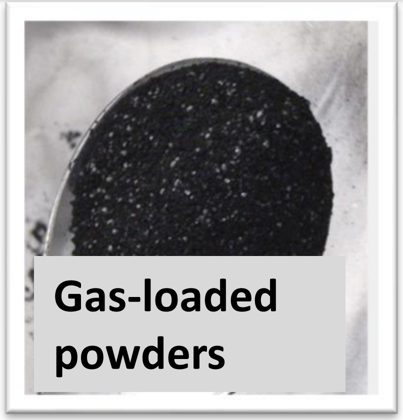
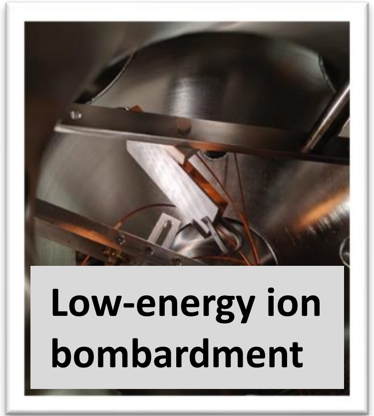








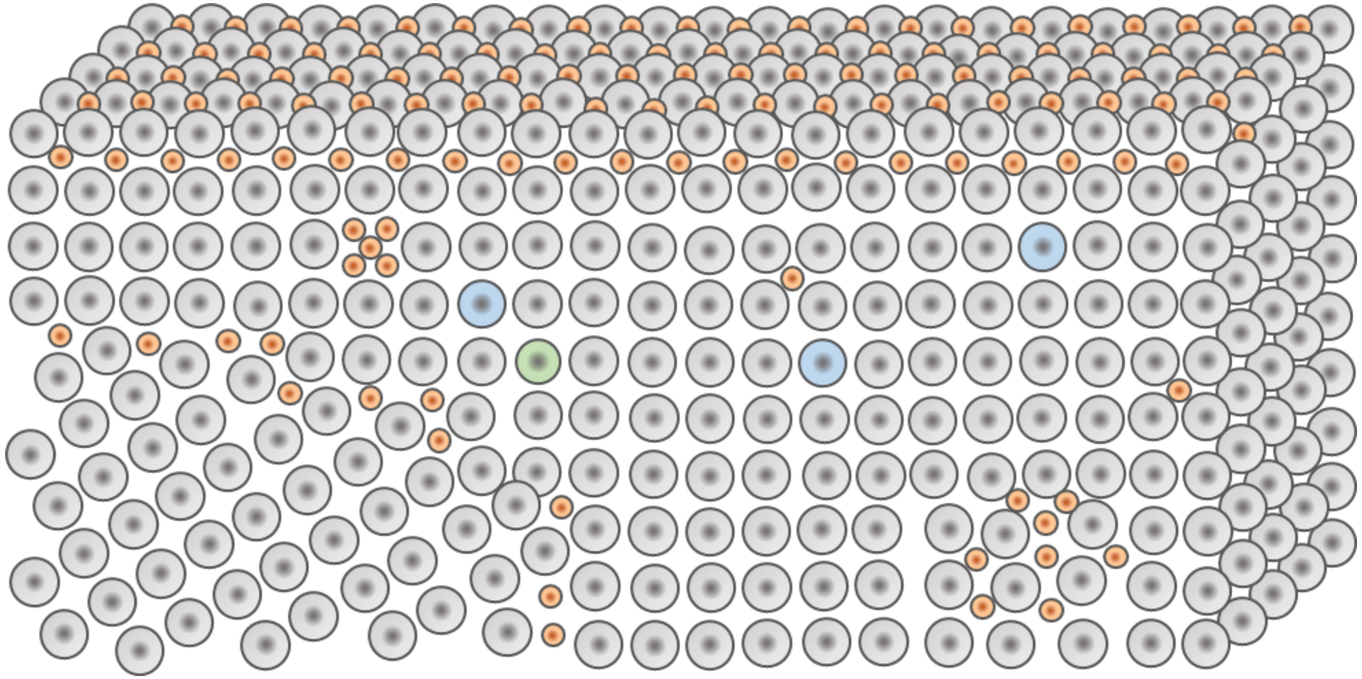
Large variety of experimental configurations

LENR experiments

LENR experiments

Common denominator at the nano level

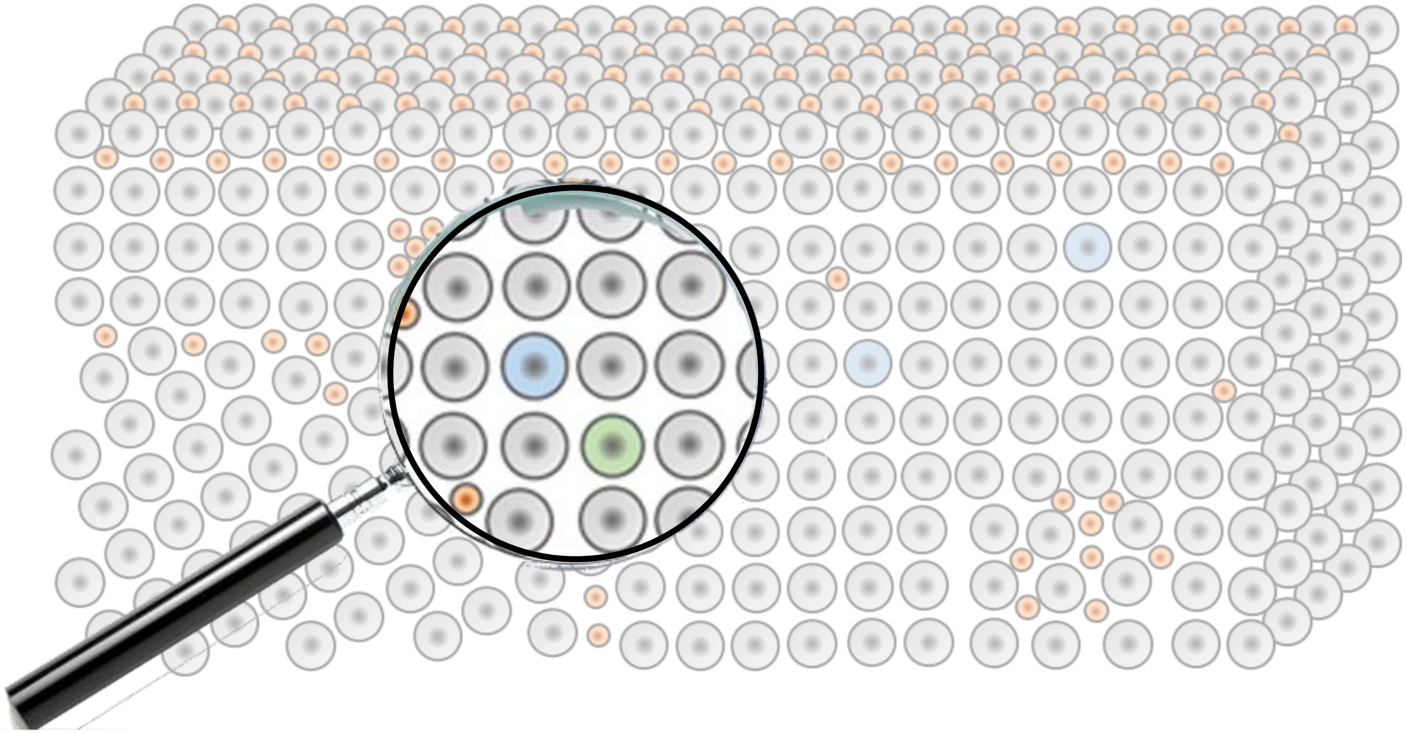
Metal-hydrogen lattice with some form of dynamical stimulation (energy in)



Common denominator at the nano level

Metal-hydrogen lattice with some form of dynamical stimulation (energy in)

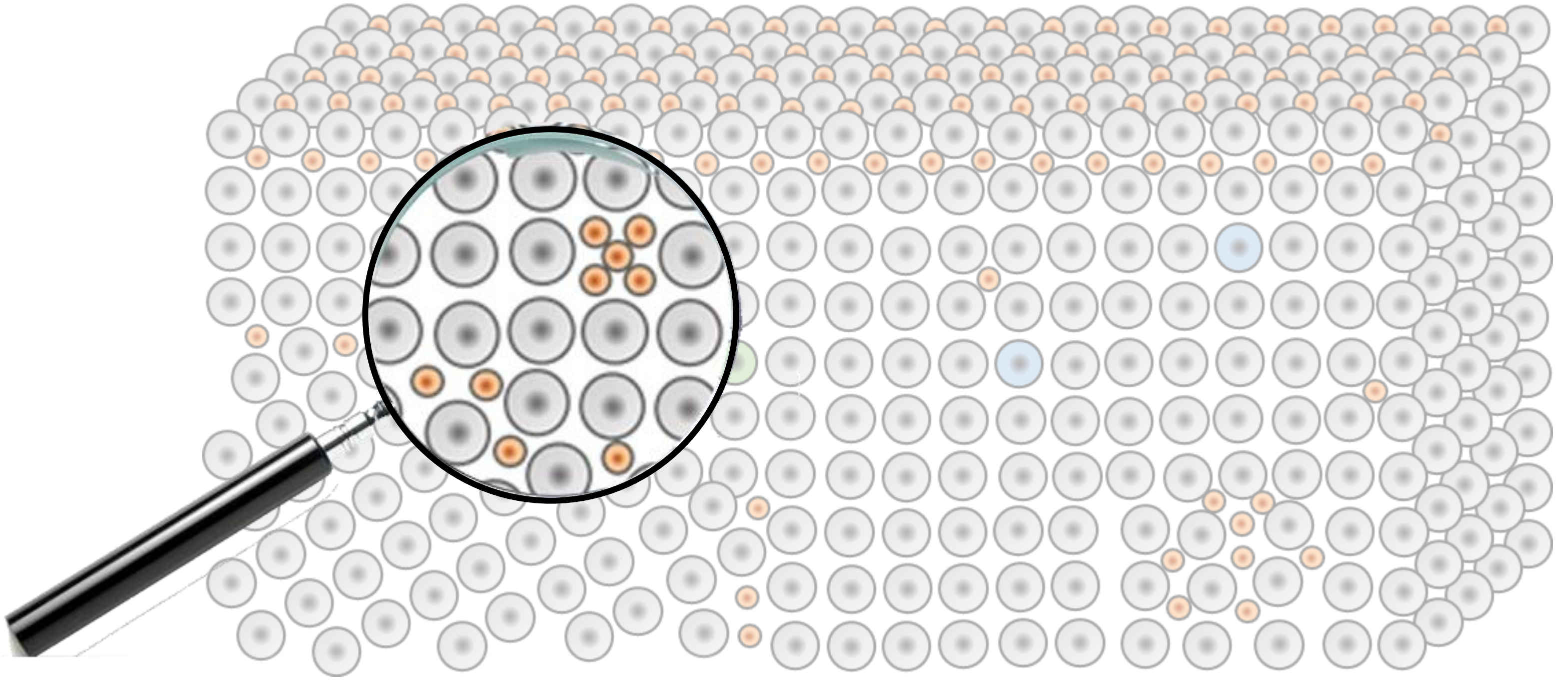
Lattice composition



Common denominator at the nano level

Metal-hydrogen lattice with some form of dynamical stimulation (energy in)

Lattice morphology

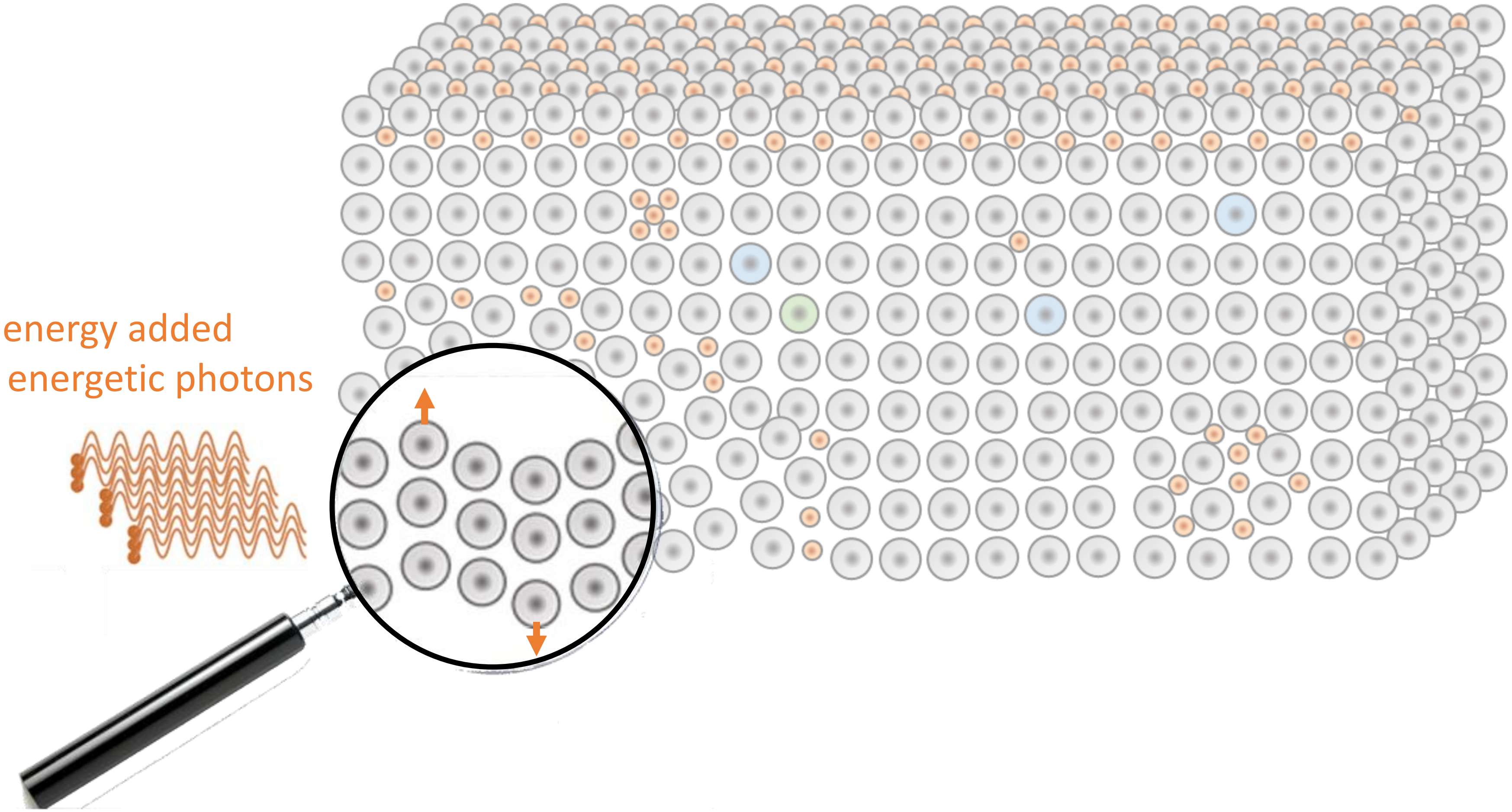


Common denominator at the nano level

Metal-hydrogen lattice with some form of dynamical stimulation (energy in)

Lattice dynamics

Kinetic energy added
e.g. via energetic photons



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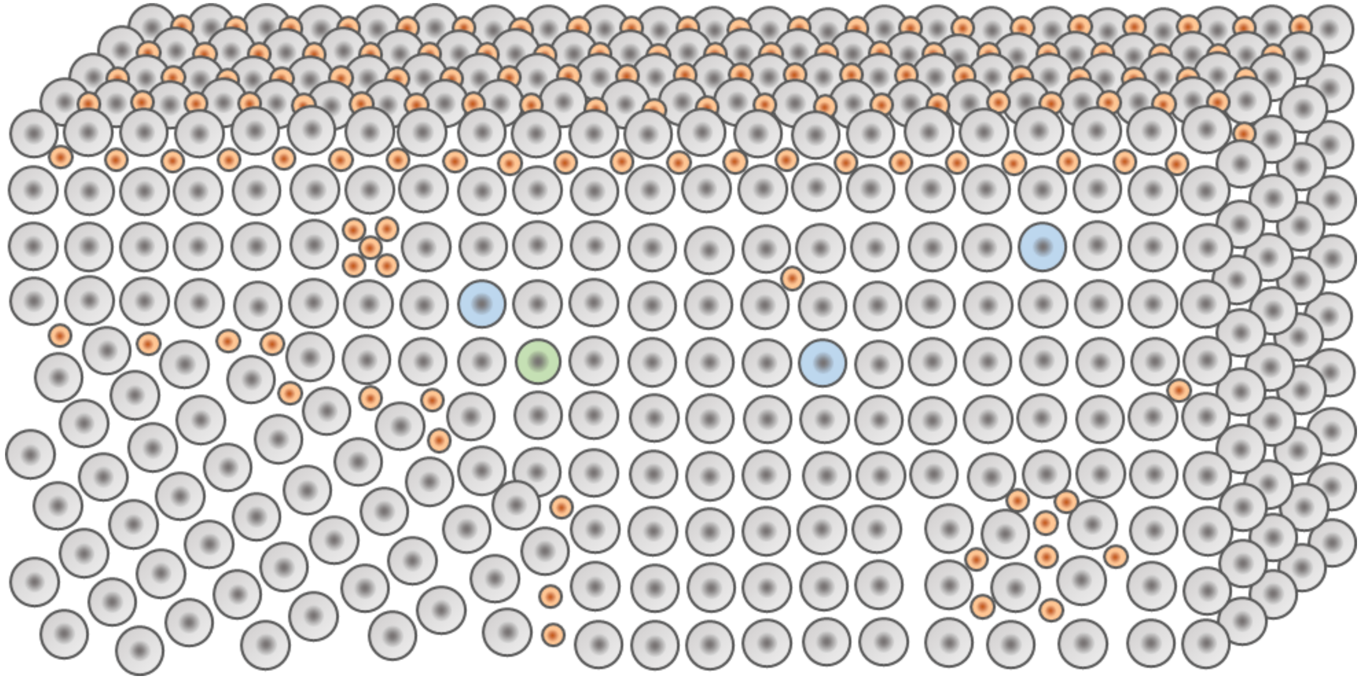
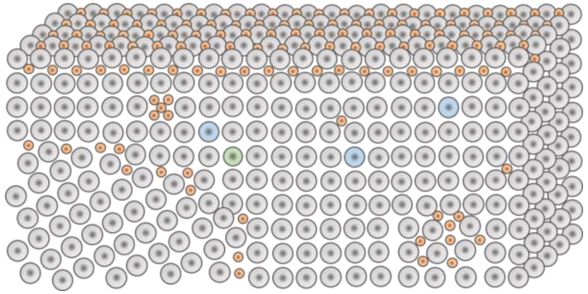
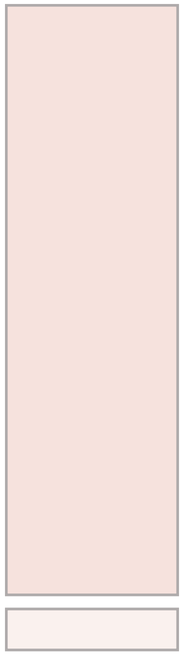


Energy balance sheet

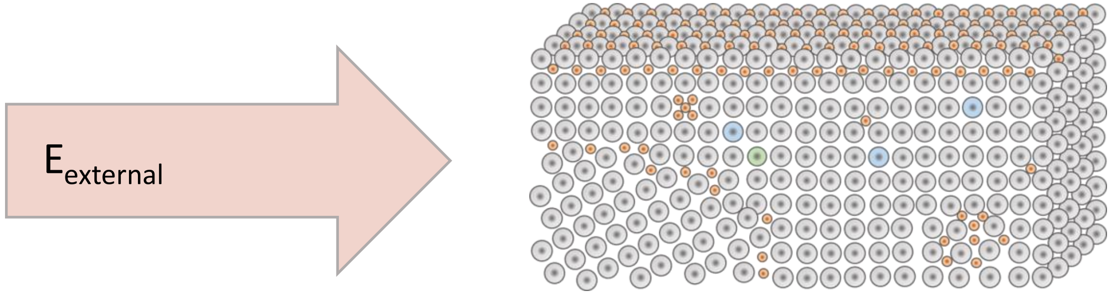




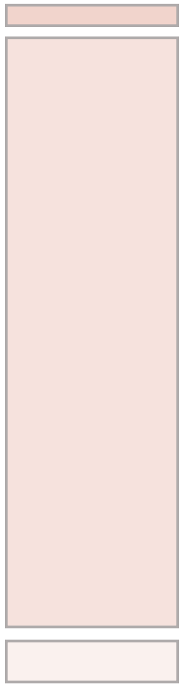
Nuclear potential energy
$E = mc^2$

Atomic potential energy

Energy balance sheet



Kinetic energy in



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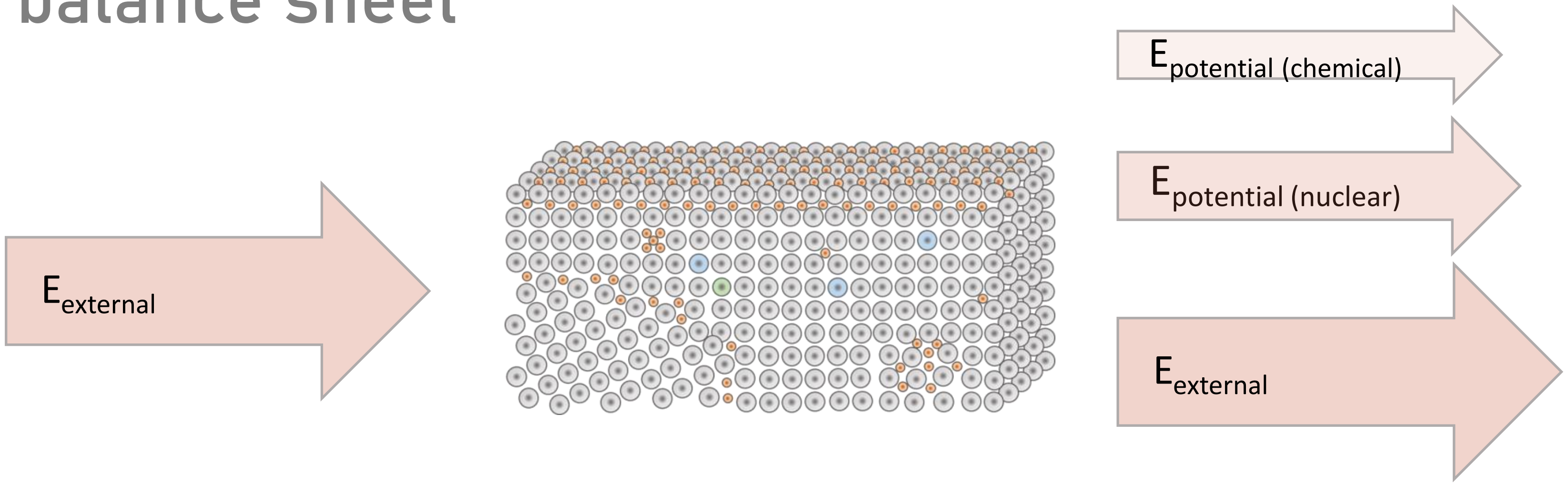

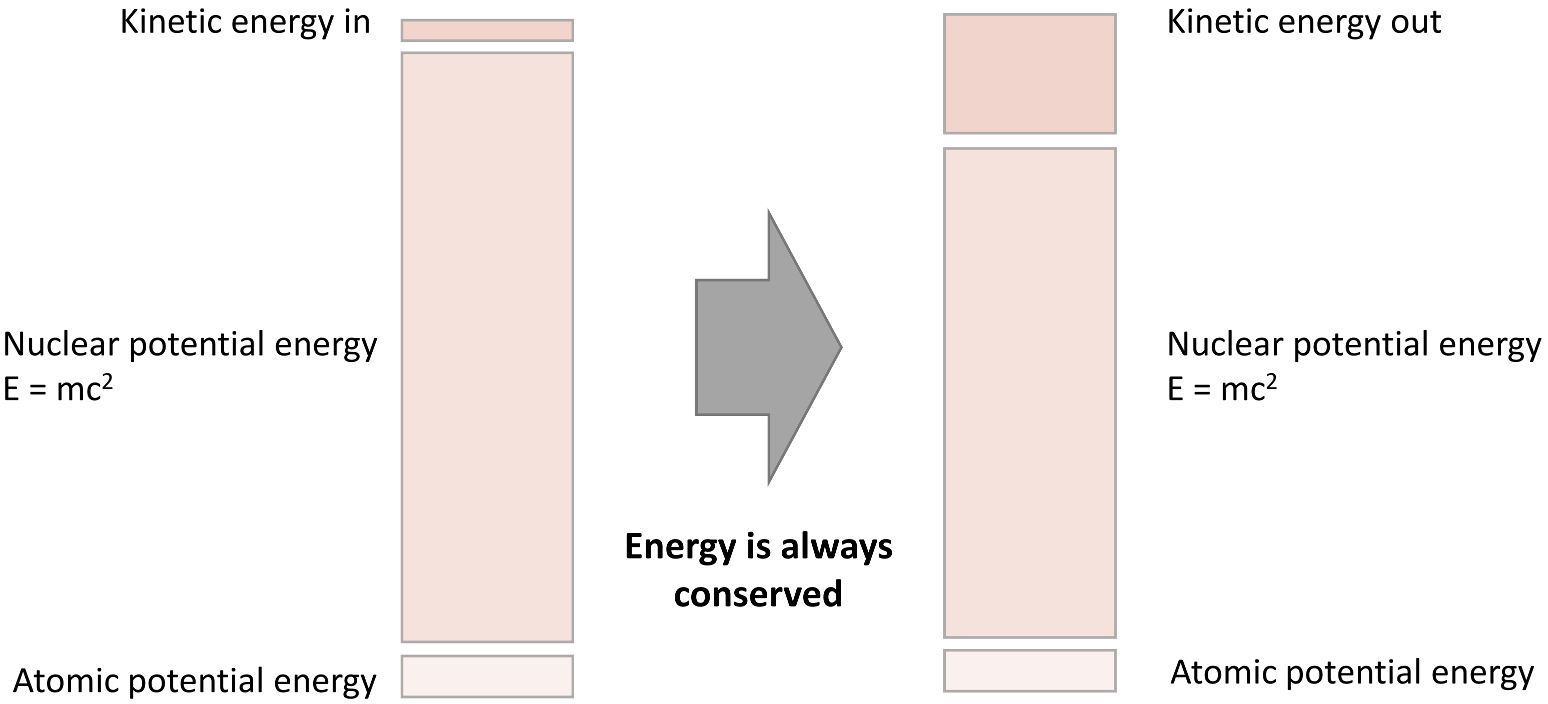

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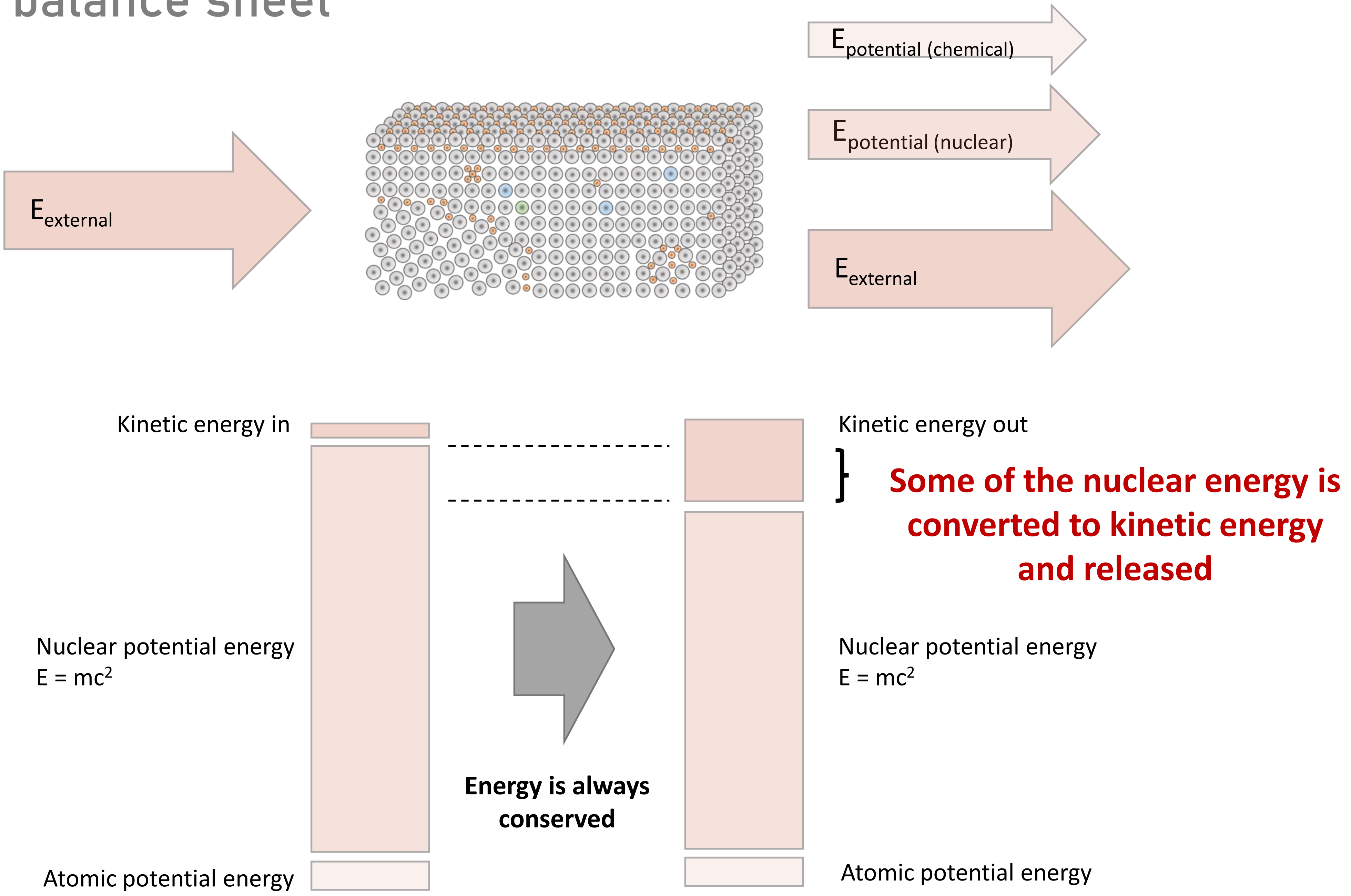
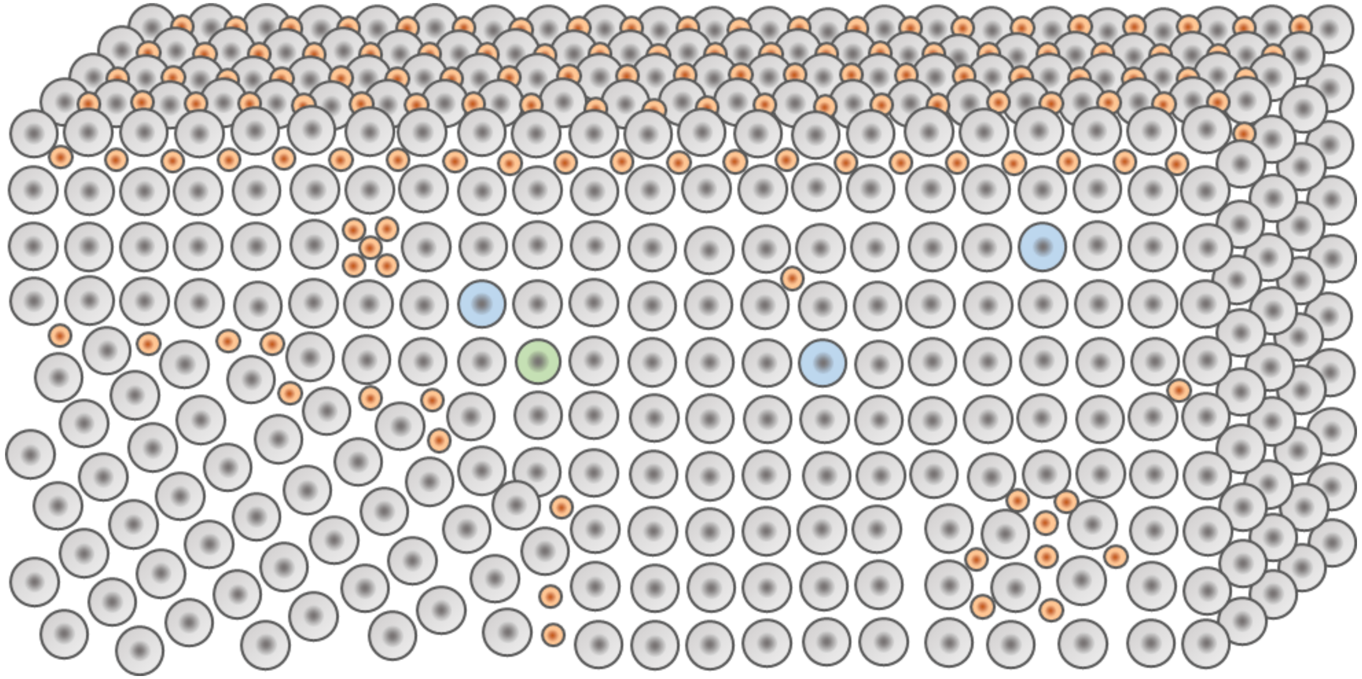


Conceivable energy release modes

Metal-hydrogen lattice with some form of nuclear energy release (energy out)



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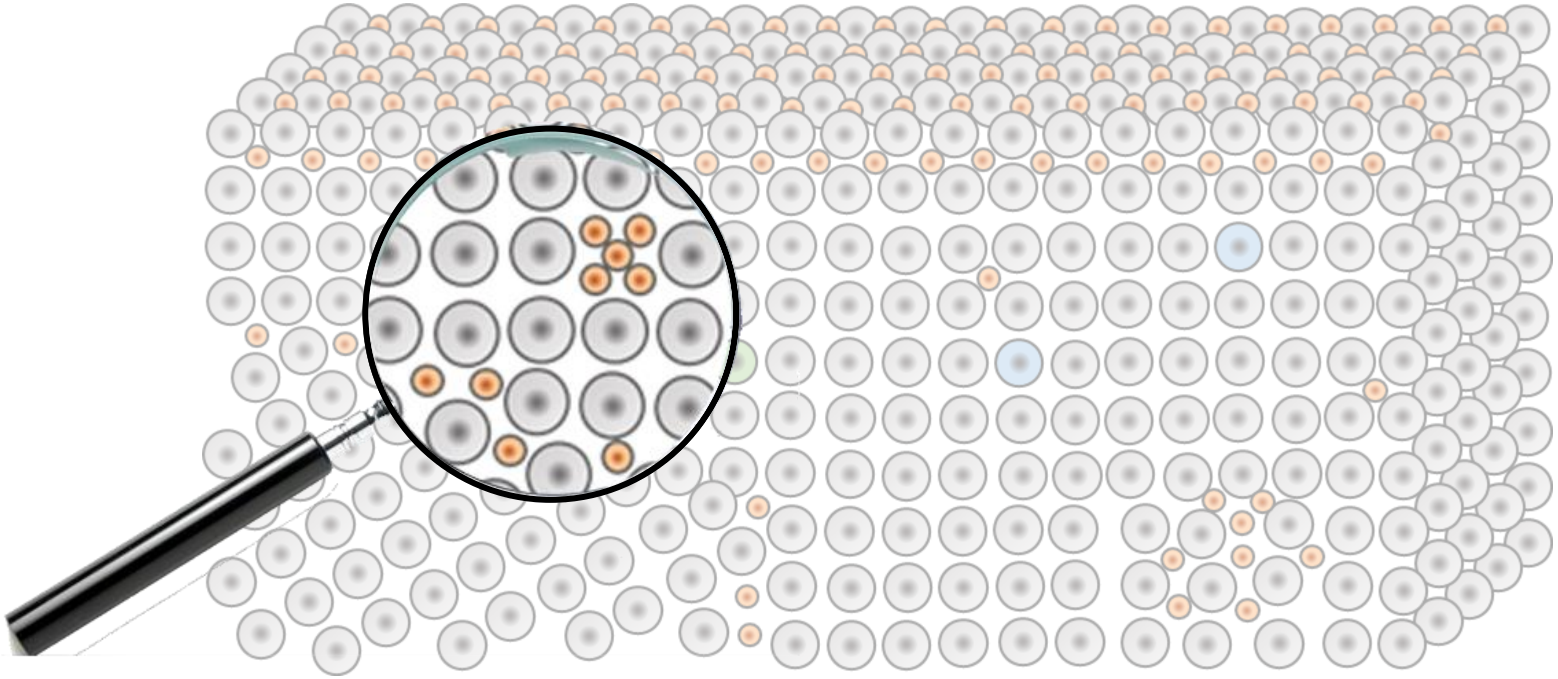

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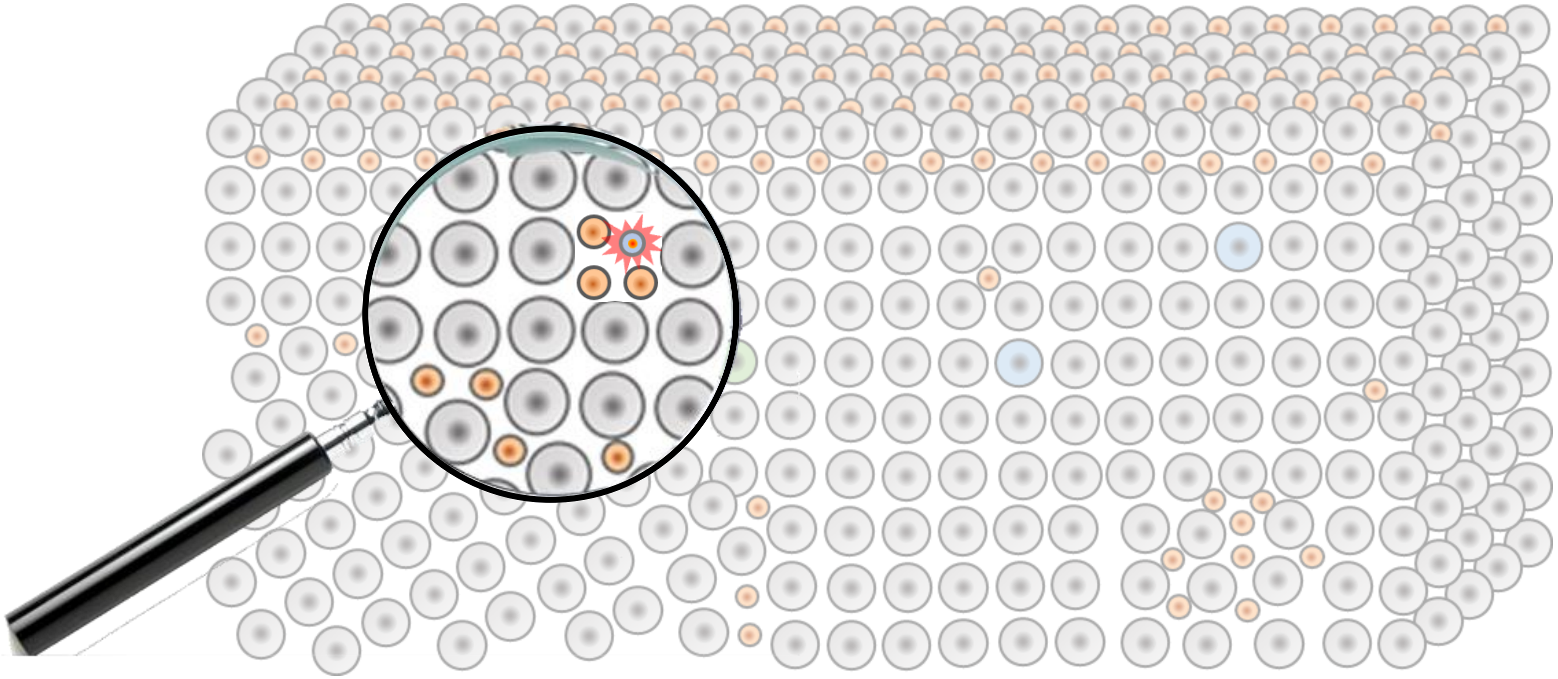

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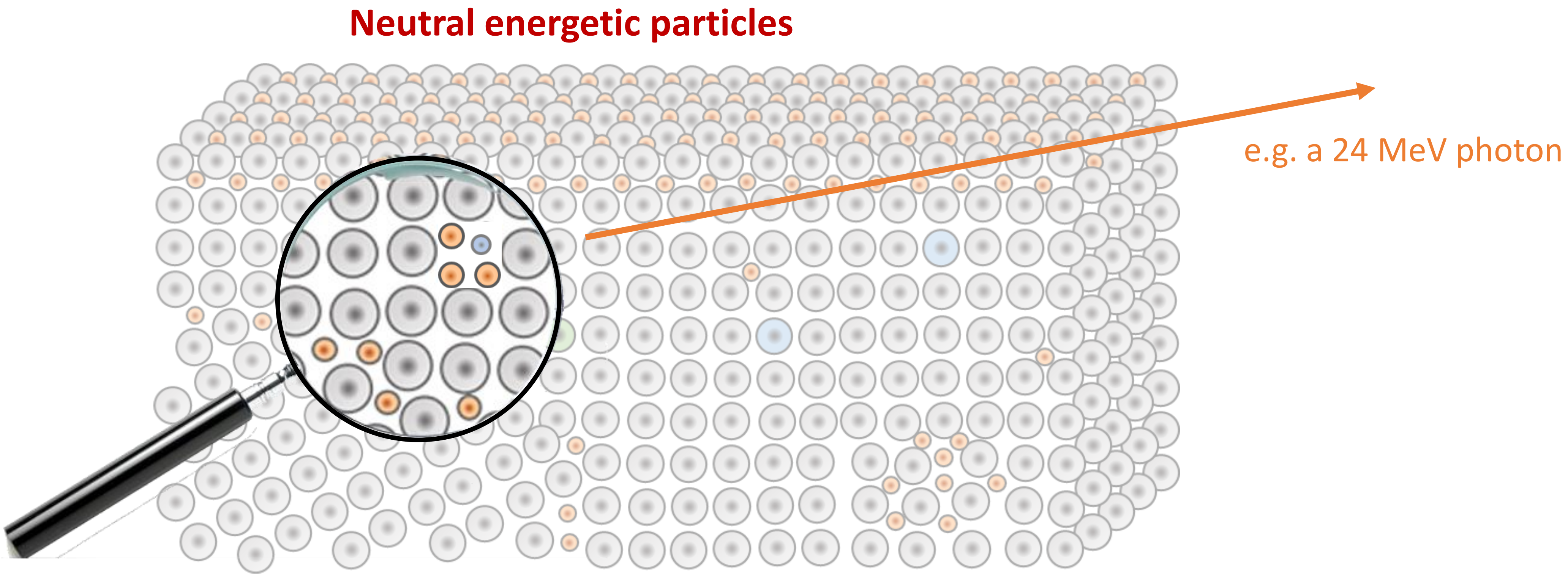

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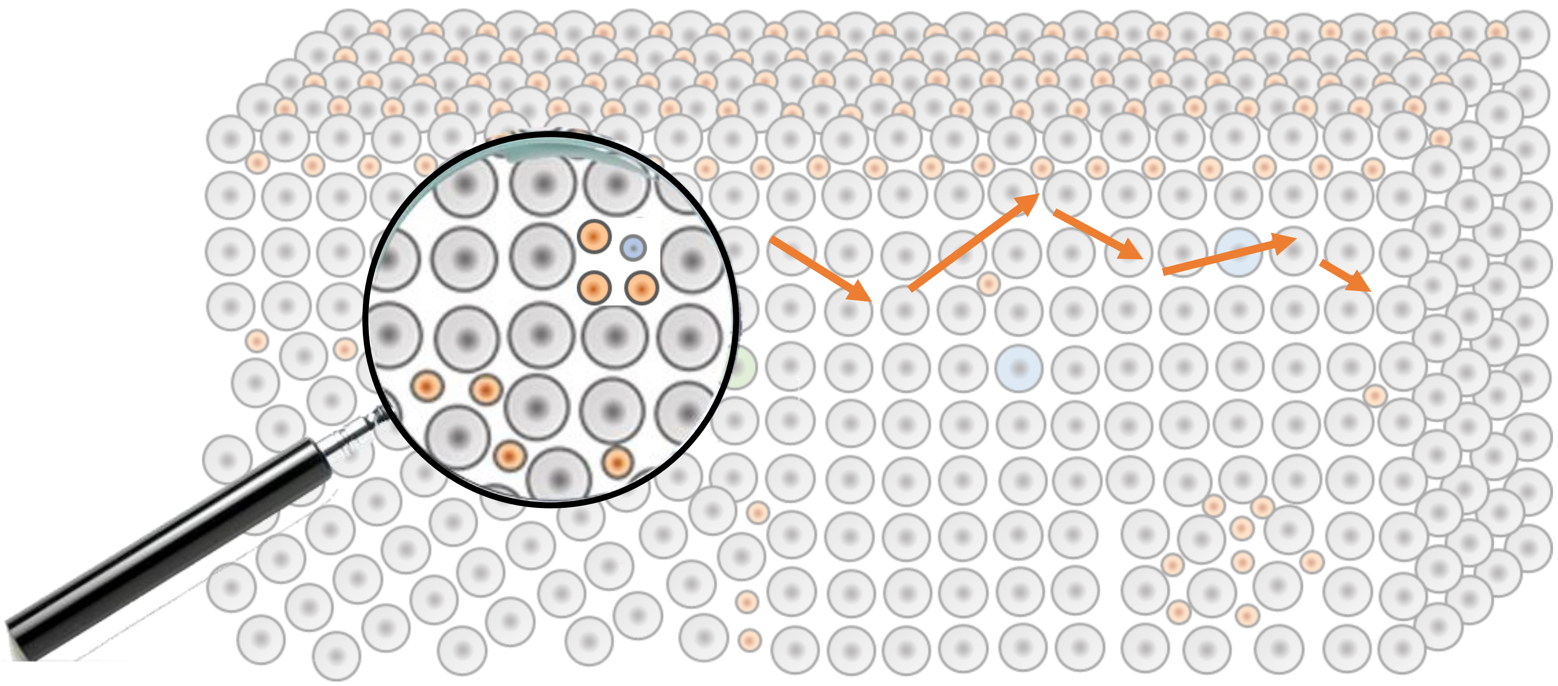
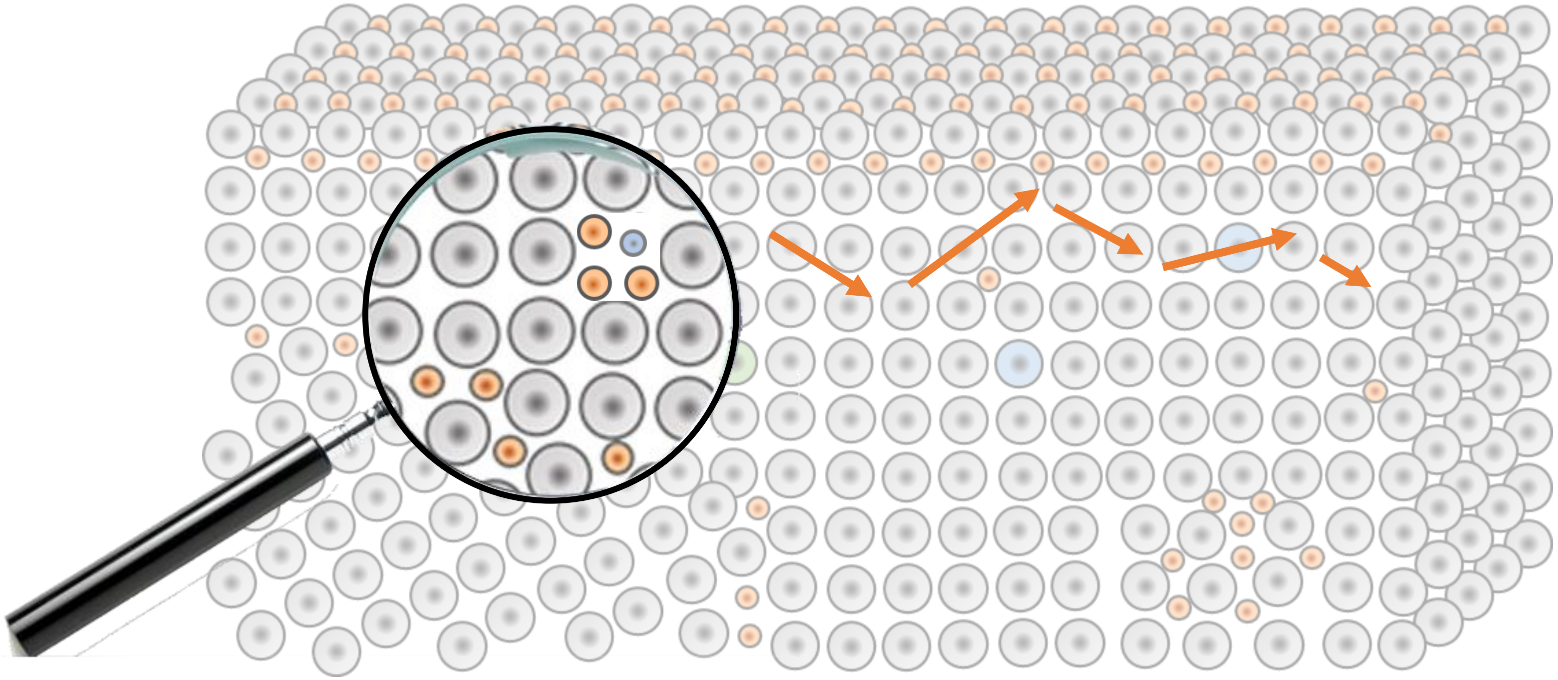


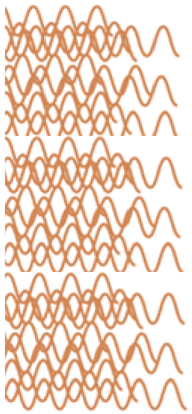
Conceivable energy release modes

Metal-hydrogen lattice with some form of nuclear energy release (energy out)

Charged energetic particles



heat



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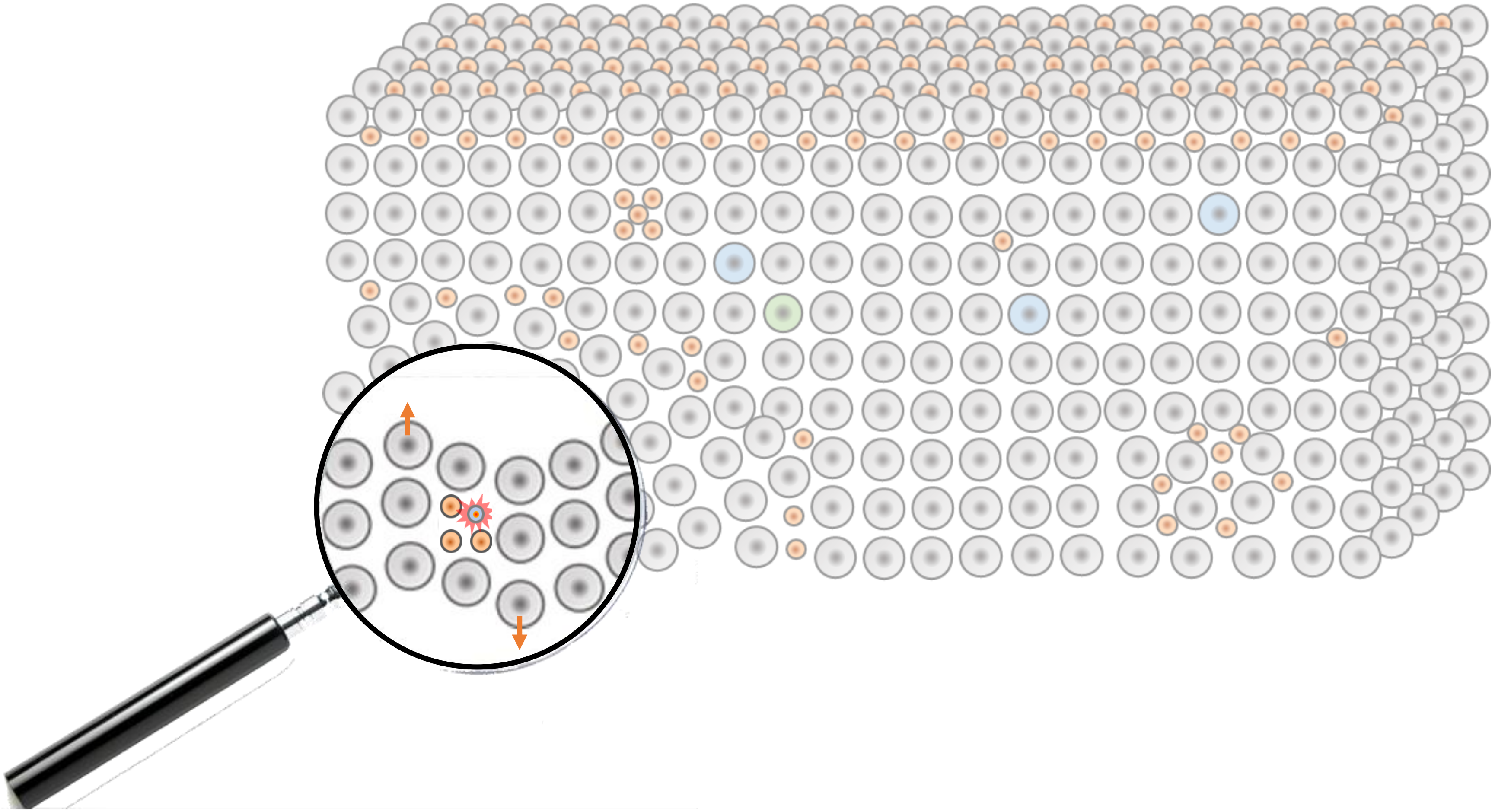
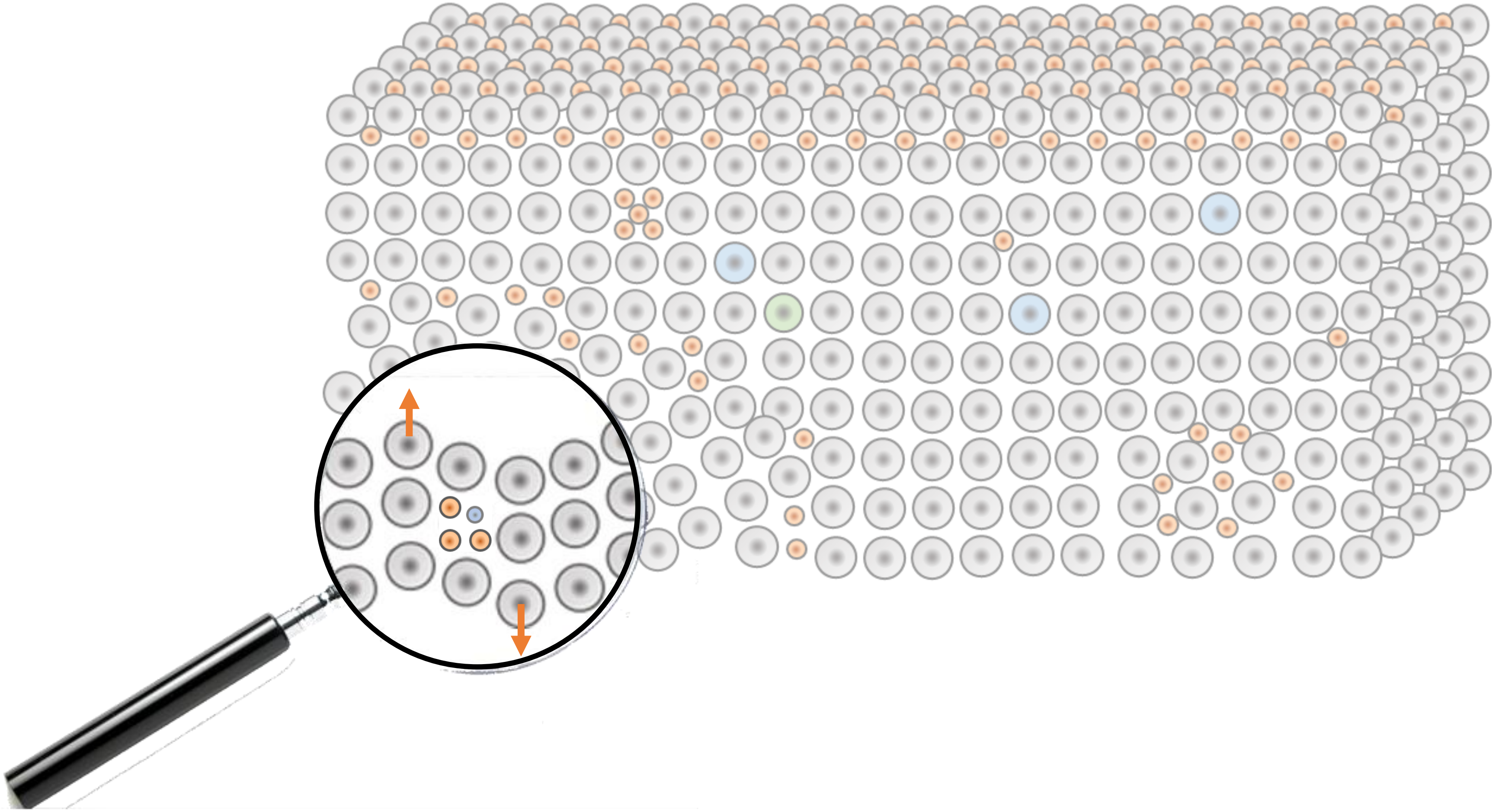


Conceivable energy release modes

Metal-hydrogen lattice with some form of nuclear energy release (energy out)

Lattice dynamics



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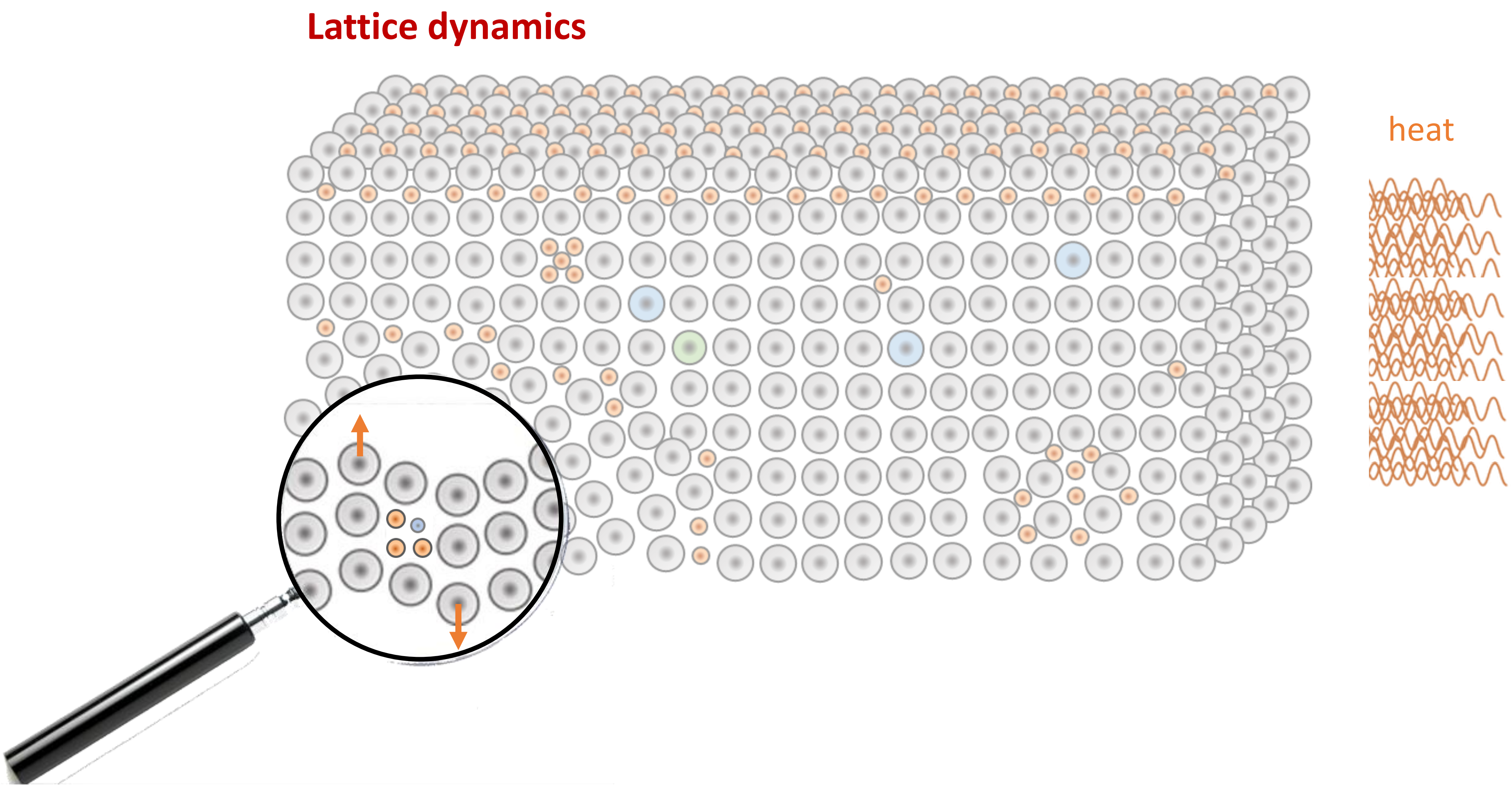

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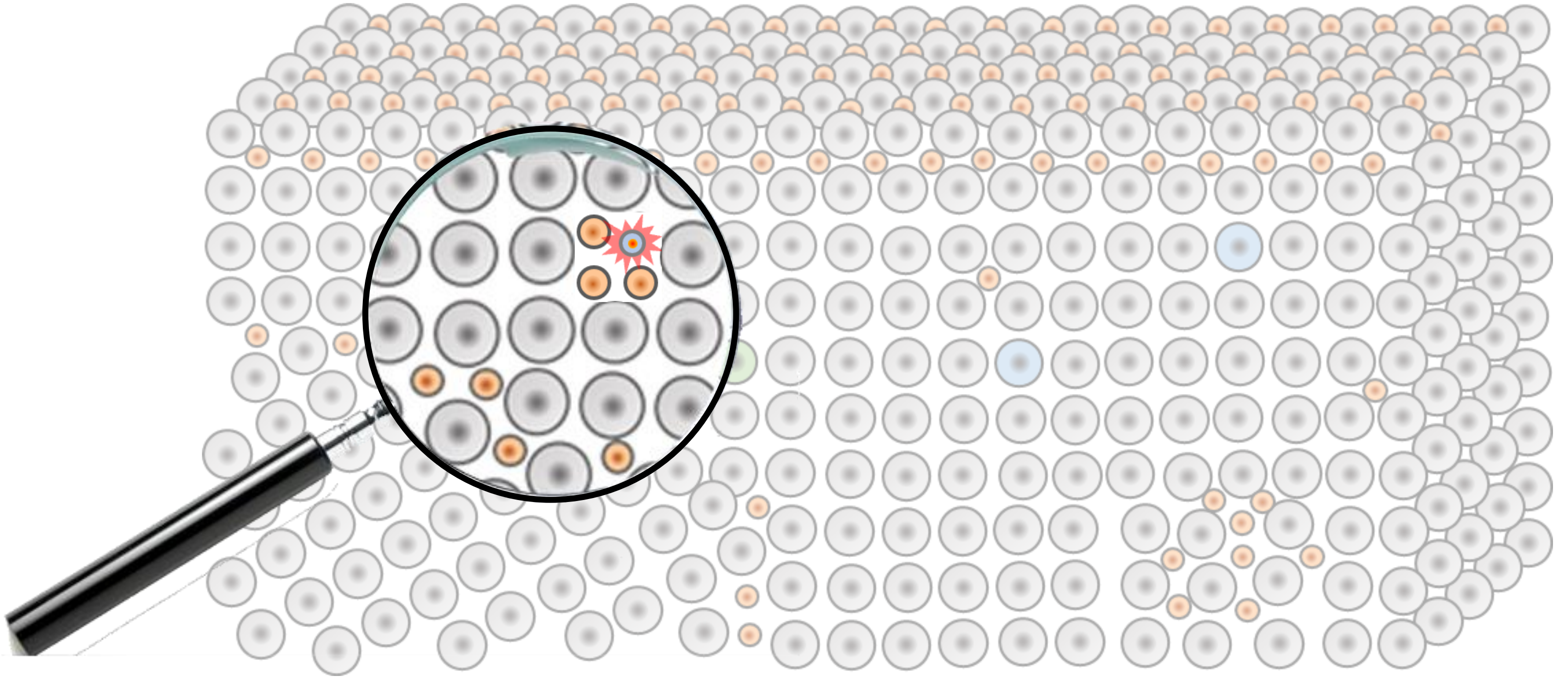
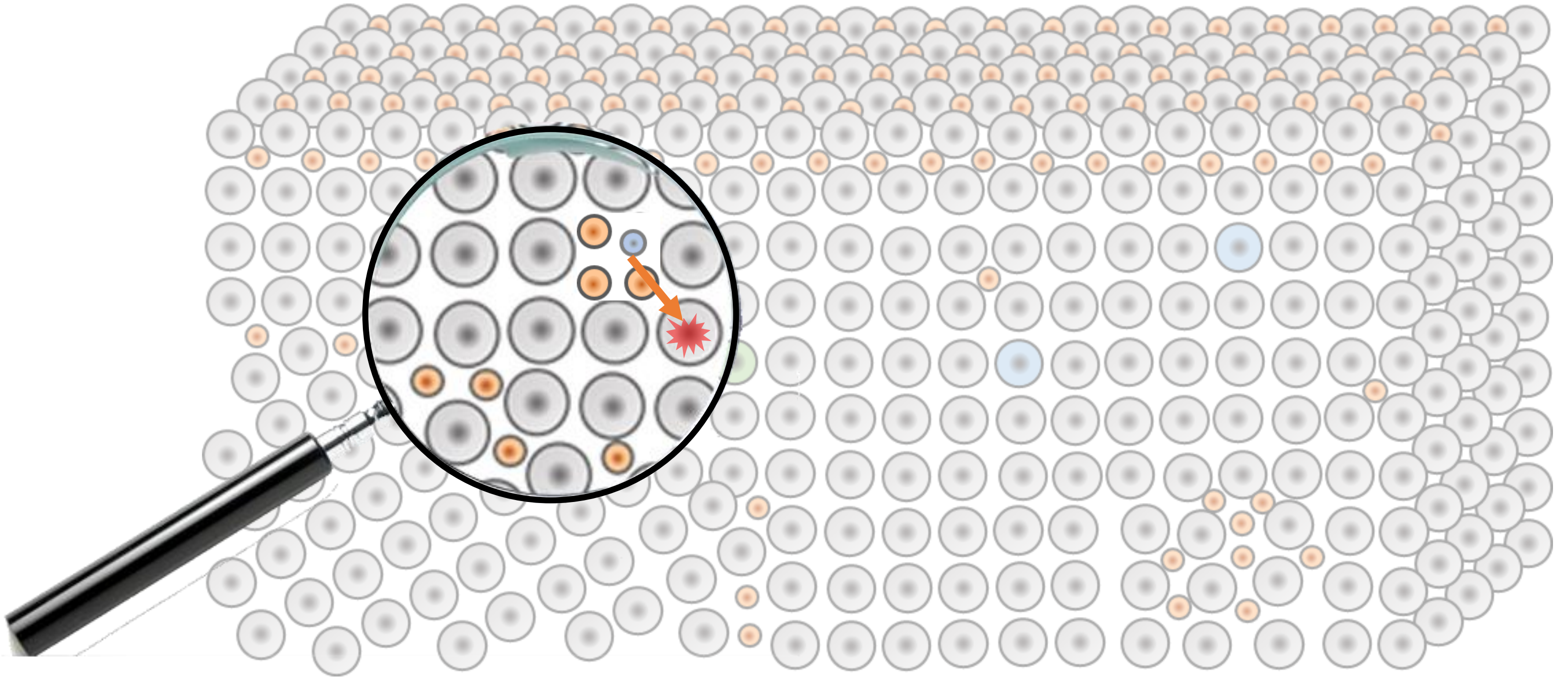


Conceivable energy release modes

Metal-hydrogen lattice with some form of nuclear energy release (energy out)

Triggering secondary nuclear reactions



Conceivable energy release modes

Metal-hydrogen lattice with some form of nuclear energy release (energy out)

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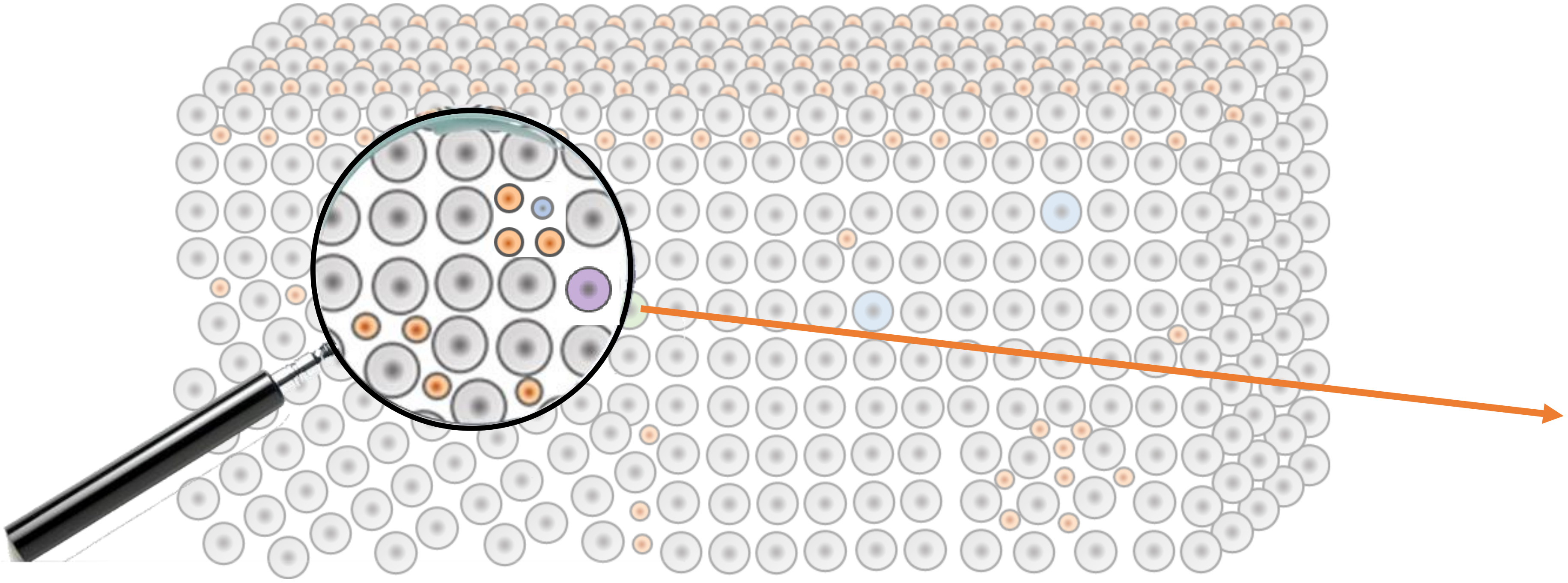

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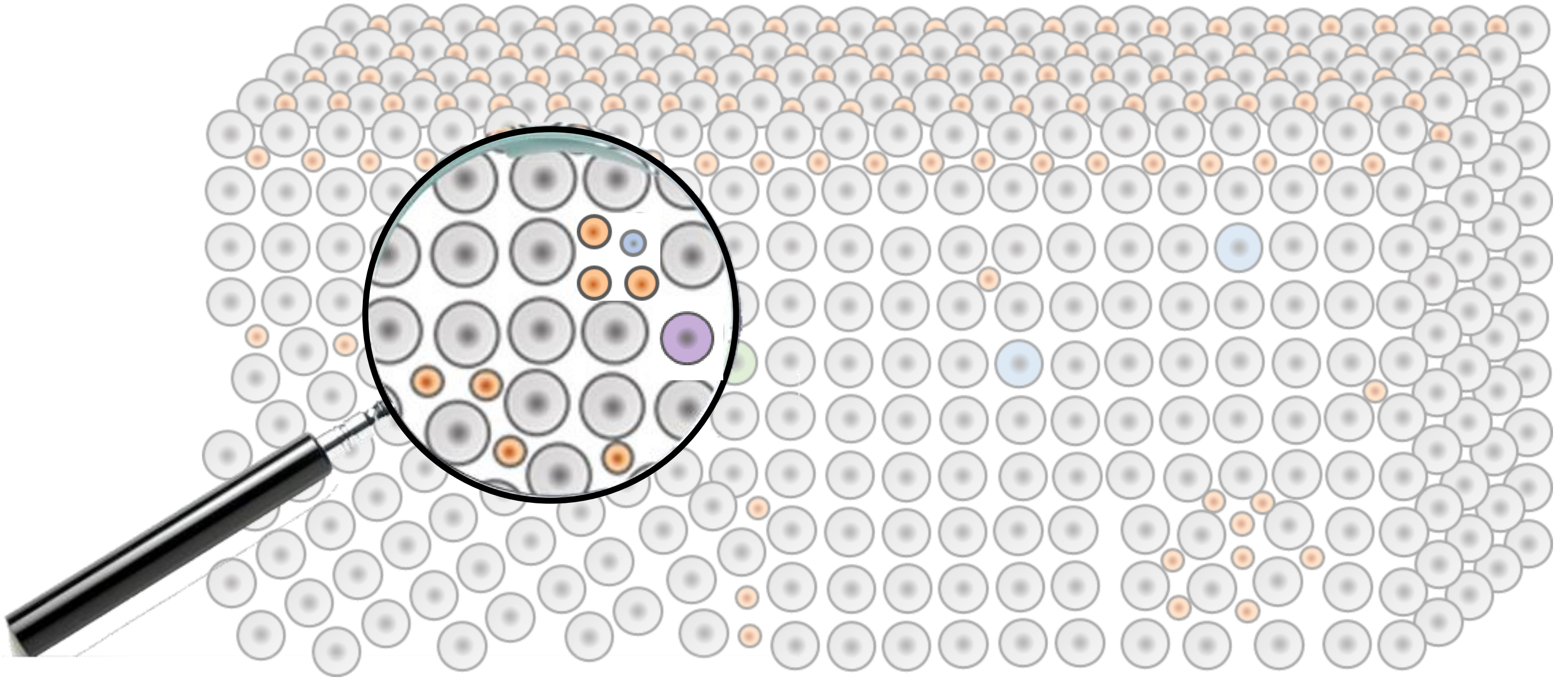

Conceivable energy release modes

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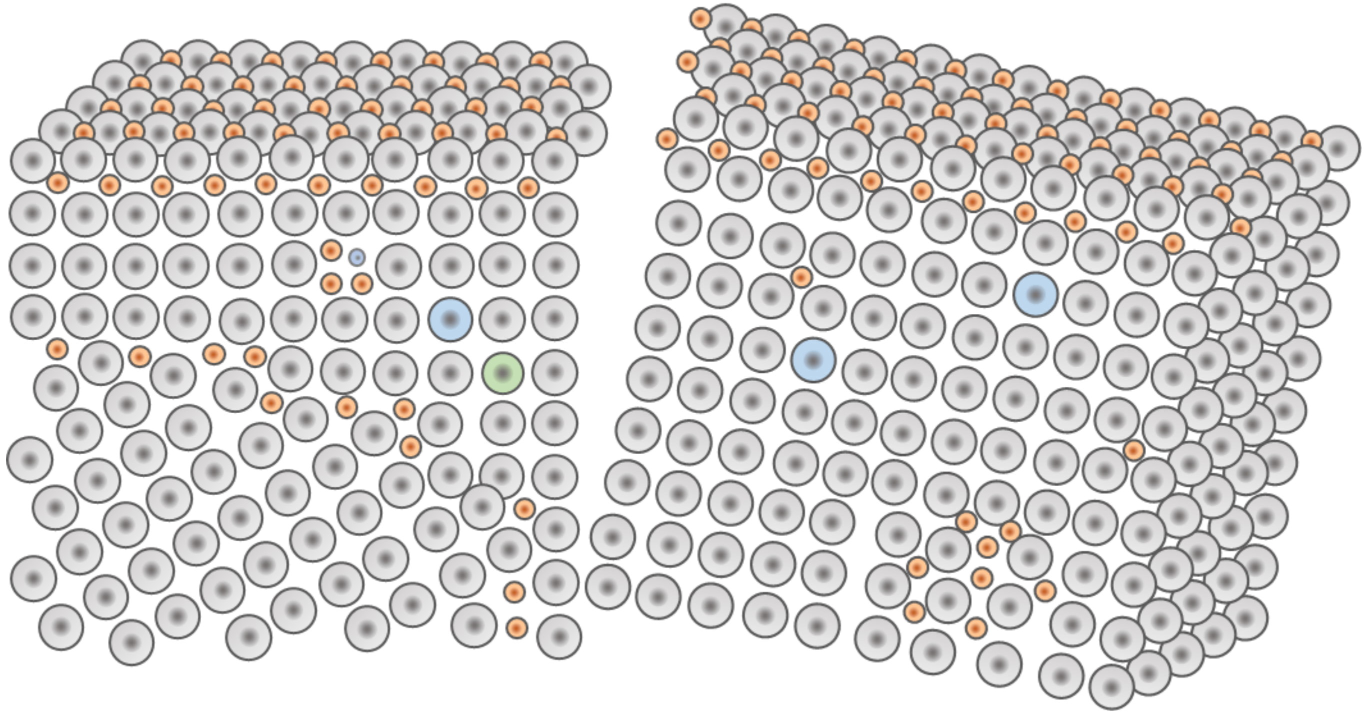
Breakage of chemical bonds



Characterization modes

HEAT

ENERGETIC PARTICLES

LATTICE COMPOSITION + CHANGES

LATTICE MORPHOLOGY + CHANGES

LATTICE DYNAMICS + CHANGES

Characterization modes

HEAT

ENERGETIC PARTICLES

LATTICE COMPOSITION + CHANGES

LATTICE MORPHOLOGY + CHANGES

LATTICE DYNAMICS + CHANGES

Alternative explanations:

Characterization modes

HEAT

ENERGETIC PARTICLES

LATTICE COMPOSITION + CHANGES

LATTICE MORPHOLOGY + CHANGES

LATTICE DYNAMICS + CHANGES

Alternative explanations:

Questions to be addressed:

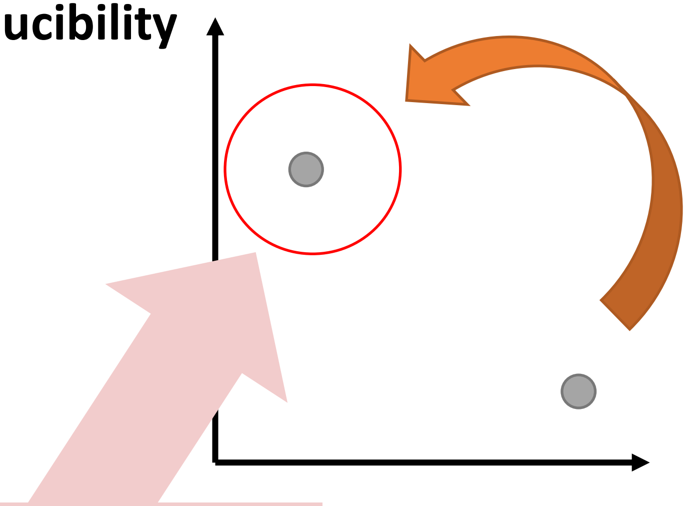
Anomaly or not?

Which reactions?

Which mechanisms?

The reproducibility challenge and the ambiguity challenge

Reproducibility



Number of
alternative explanations

Goal: high producibility, low ambiguity
How to get there?

B2. Characterization modes by example

	Fleischmann & Pons 1990	Swartz 2015	Jones et al. 1990	Chambers et al. 1990	Forbes et al. 2019	Gozzi et al. 1998	Biberian 2020	Fralick et al. 2020	Kitamura et al. 2018	Letts et al. 2010	Swartz et al. 2017
HEAT	20 MJ in 80 d from 2 g of PdD	2 KJ in 1 d from 0.2 g of PdD	?	?	?	8 MJ in 38 d from 6 g of PdD	?	? T rise but no calorimetry	23 MJ in 60 d from 25 g PdNiD	37 x 0.5 d runs with 0-0.3 W W_{excess} from 0.1 g of PdD	?
ENERGETIC PARTICLES	?	?	5 MeV neutrons	21 MeV charged particles	28 MeV charged particles	X-ray film exposure, ?	?	?	?	?	?
LATTICE COMPOSITION	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Ti, D, P, ?	Pd, D, P, ?	Pd, Si, D, P, ?	Pd, Ag, Fe, Si, Al, D, P, ?	Pd, Ni, Zr, D, P, ?	Pd, D, P, ?	Pd, Zr, D, P, ?
+ CHANGES	?	?	?	?	?	He-4 production	Fe, Ni, Cu, Zn, Mn/Cr production	Fe, Ni, Cu, Zn, Cr production	?	?	?
LATTICE MORPHOLOGY	?	?	?	?	?	?	?	?	?	?	?
+ CHANGES	?	?	?	?	?	?	Spot formation	Spot formation	Cracks	?	?
LATTICE DYNAMICS	Uncontrolled hydrogen diffusion	Uncontrolled electric discharge	Uncontrolled hydrogen diffusion	~100 eV bombard-ment	~100 eV bombard-ment	Uncontrolled Hydrogen diffusion	Optical laser irradiation	Uncontrolled hydrogen diffusion	Uncontrolled hydrogen diffusion	Controlled THz photon stimulation	Uncontrolled electric discharge
+ CHANGES	?	?	?	?	?	?	?	?	?	?	5 THz PdD Raman peaks

	Fleischmann & Pons 1990	Swartz 2015	Jones et al. 1990	Chambers et al. 1990	Forbes et al. 2019	Gozzi et al. 1998	Biberian 2020	Fralick et al. 2020	Kitamura et al. 2018	Letts et al. 2010	Swartz et al. 2017
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ENERGETIC PARTICLES	?	?	5 MeV neutrons	21 MeV charged particles	28 MeV charged particles	X-ray film exposure, ?	?	?	?	?	?
LATTICE COMPOSITION	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Ti, D, P, ?	Pd, D, P, ?	Pd, Si, D, P, ?	Pd, Ag, Fe, Si, Al, D, P, ?	Pd, Ni, Zr, D, P, ?	Pd, D, P, ?	Pd, Zr, D, P, ?
+ CHANGES	?	?	?	?	?	He-4 production	Fe, Ni, Cu, Zn, Mn/Cr production	Fe, Ni, Cu, Zn, Cr production	?	?	?
LATTICE MORPHOLOGY	?	?	?	?	?	?	?	?	?	?	?
+ CHANGES	?	?	?	?	?	?	Spot formation	Spot formation	Cracks	?	?
LATTICE DYNAMICS	Uncontrolled hydrogen diffusion	Uncontrolled electric discharge	Uncontrolled hydrogen diffusion	~100 eV bombard-ment	~100 eV bombard-ment	Uncontrolled Hydrogen diffusion	Optical laser irradiation	Uncontrolled hydrogen diffusion	Uncontrolled hydrogen diffusion	Controlled THz photon stimulation	Uncontrolled electric discharge
+ CHANGES	?	?	?	?	?	?	?	?	?	?	5 THz PdD Raman peaks

	Fleischmann & Pons 1990	Swartz 2015	Jones et al. 1990	Chambers et al. 1990	Forbes et al. 2019	Gozzi et al. 1998	Biberian 2020	Fralick et al. 2020	Kitamura et al. 2018	Letts et al. 2010	Swartz et al. 2017
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ENERGETIC PARTICLES	?	?	5 MeV neutrons	21 MeV charged particles	28 MeV charged particles	X-ray film exposure, ?	?	?	?	?	?
LATTICE COMPOSITION	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Ti, D, P, ?	Pd, D, P, ?	Pd, Si, D, P, ?	Pd, Ag, Fe, Si, Al, D, P, ?	Pd, Ni, Zr, D, P, ?	Pd, D, P, ?	Pd, Zr, D, P, ?
+ CHANGES	?	?	?	?	?	He-4 production	Fe, Ni, Cu, Zn, Mn/Cr production	Fe, Ni, Cu, Zn, Cr production	?	?	?
LATTICE MORPHOLOGY	?	?	?	?	?	?	?	?	?	?	?
+ CHANGES	?	?	?	?	?	?	Spot formation	Spot formation	Cracks	?	?
LATTICE DYNAMICS	Uncontrolled hydrogen diffusion	Uncontrolled electric discharge	Uncontrolled hydrogen diffusion	~100 eV bombard-ment	~100 eV bombard-ment	Uncontrolled Hydrogen diffusion	Optical laser irradiation	Uncontrolled hydrogen diffusion	Uncontrolled hydrogen diffusion	Controlled THz photon stimulation	Uncontrolled electric discharge
+ CHANGES	?	?	?	?	?	?	?	?	?	?	5 THz PdD Raman peaks

	Fleischmann & Pons 1990	Swartz 2015	Jones et al. 1990	Chambers et al. 1990	Forbes et al. 2019	Gozzi et al. 1998	Biberian 2020	Fralick et al. 2020	Kitamura et al. 2018	Letts et al. 2010	Swartz et al. 2017
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ENERGETIC PARTICLES	?	?	5 MeV neutrons	21 MeV charged particles	28 MeV charged particles	X-ray film exposure, ?	?	?	?	?	?
LATTICE COMPOSITION	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Ti, D, P, ?	Pd, D, P, ?	Pd, Si, D, P, ?	Pd, Ag, Fe, Si, Al, D, P, ?	Pd, Ni, Zr, D, P, ?	Pd, D, P, ?	Pd, Zr, D, P, ?
+ CHANGES	?	?	?	?	?	He-4 production	Fe, Ni, Cu, Zn, Mn/Cr production	Fe, Ni, Cu, Zn, Cr production	?	?	?
LATTICE MORPHOLOGY	?	?	?	?	?	?	?	?	?	?	?
+ CHANGES	?	?	?	?	?	?	Spot formation	Spot formation	Cracks	?	?
LATTICE DYNAMICS	Uncontrolled hydrogen diffusion	Uncontrolled electric discharge	Uncontrolled hydrogen diffusion	~100 eV bombard-ment	~100 eV bombard-ment	Uncontrolled Hydrogen diffusion	Optical laser irradiation	Uncontrolled hydrogen diffusion	Uncontrolled hydrogen diffusion	Controlled THz photon stimulation	Uncontrolled electric discharge
+ CHANGES	?	?	?	?	?	?	?	?	?	?	5 THz PdD Raman peaks

	Fleischmann & Pons 1990	Swartz 2015	Jones et al. 1990	Chambers et al. 1990	Forbes et al. 2019	Gozzi et al. 1998	Biberian 2020	Fralick et al. 2020	Kitamura et al. 2018	Letts et al. 2010	Swartz et al. 2017
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ENERGETIC PARTICLES	?	?	5 MeV neutrons	21 MeV charged particles	28 MeV charged particles	X-ray film exposure, ?	?	?	?	?	?
LATTICE COMPOSITION	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Ti, D, P, ?	Pd, D, P, ?	Pd, Si, D, P, ?	Pd, Ag, Fe, Si, Al, D, P, ?	Pd, Ni, Zr, D, P, ?	Pd, D, P, ?	Pd, Zr, D, P, ?
+ CHANGES	?	?	?	?	?	He-4 production	Fe, Ni, Cu, Zn, Mn/Cr production	Fe, Ni, Cu, Zn, Cr production	?	?	?
LATTICE MORPHOLOGY	?	?	?	?	?	?	?	?	?	?	?
+ CHANGES	?	?	?	?	?	?	Spot formation	Spot formation	Cracks	?	?
LATTICE DYNAMICS	Uncontrolled hydrogen diffusion	Uncontrolled electric discharge	Uncontrolled hydrogen diffusion	~100 eV bombard-ment	~100 eV bombard-ment	Uncontrolled Hydrogen diffusion	Optical laser irradiation	Uncontrolled hydrogen diffusion	Uncontrolled hydrogen diffusion	Controlled THz photon stimulation	Uncontrolled electric discharge
+ CHANGES	?	?	?	?	?	?	?	?	?	?	5 THz PdD Raman peaks

	Fleischmann & Pons 1990	Swartz 2015	Jones et al. 1990	Chambers et al. 1990	Forbes et al. 2019	Gozzi et al. 1998	Biberian 2020	Fralick et al. 2020	Kitamura et al. 2018	Letts et al. 2010	Swartz et al. 2017
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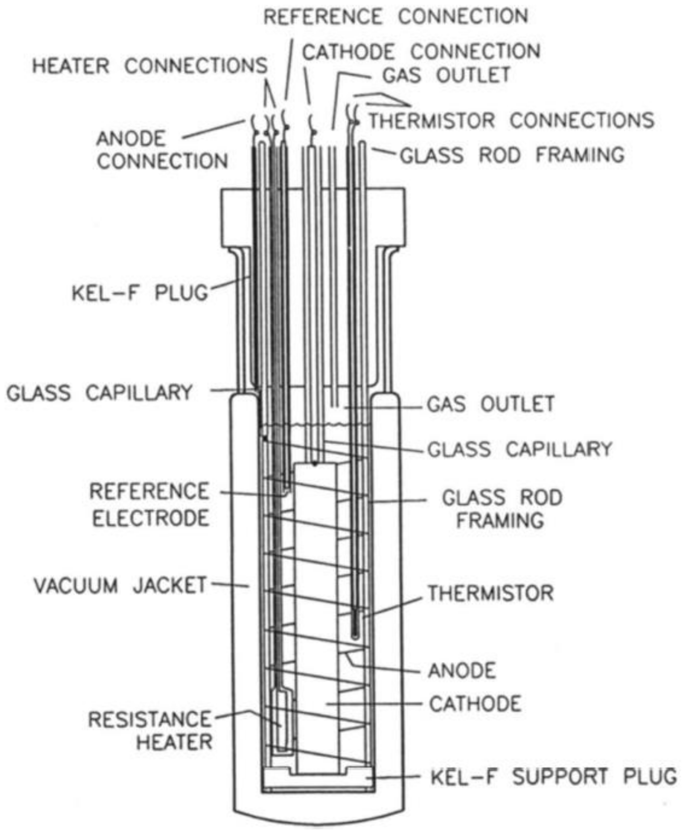
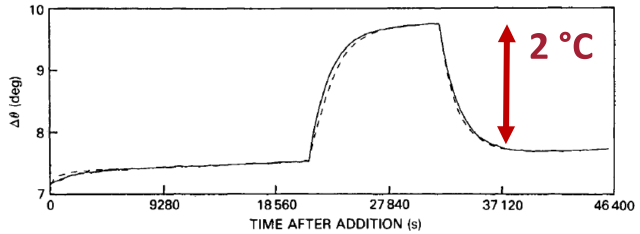
ENERGETIC PARTICLES	?	?	5 MeV neutrons	21 MeV charged particles	28 MeV charged particles	X-ray film exposure, ?	?	?	?	?	?
LATTICE COMPOSITION	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Ti, D, P, ?	Pd, D, P, ?	Pd, Si, D, P, ?	Pd, Ag, Fe, Si, Al, D, P, ?	Pd, Ni, Zr, D, P, ?	Pd, D, P, ?	Pd, Zr, D, P, ?
+ CHANGES	?	?	?	?	?	He-4 production	Fe, Ni, Cu, Zn, Mn/Cr production	Fe, Ni, Cu, Zn, Cr production	?	?	?
LATTICE MORPHOLOGY	?	?	?	?	?	?	?	?	?	?	?
+ CHANGES	?	?	?	?	?	?	Spot formation	Spot formation	Cracks	?	?
LATTICE DYNAMICS	Uncontrolled hydrogen diffusion	Uncontrolled electric discharge	Uncontrolled hydrogen diffusion	~100 eV bombard-ment	~100 eV bombard-ment	Uncontrolled Hydrogen diffusion	Optical laser irradiation	Uncontrolled hydrogen diffusion	Uncontrolled hydrogen diffusion	Controlled THz photon stimulation	Uncontrolled electric discharge
+ CHANGES	?	?	?	?	?	?	?	?	?	?	5 THz PdD Raman peaks

Characterization mode: heat

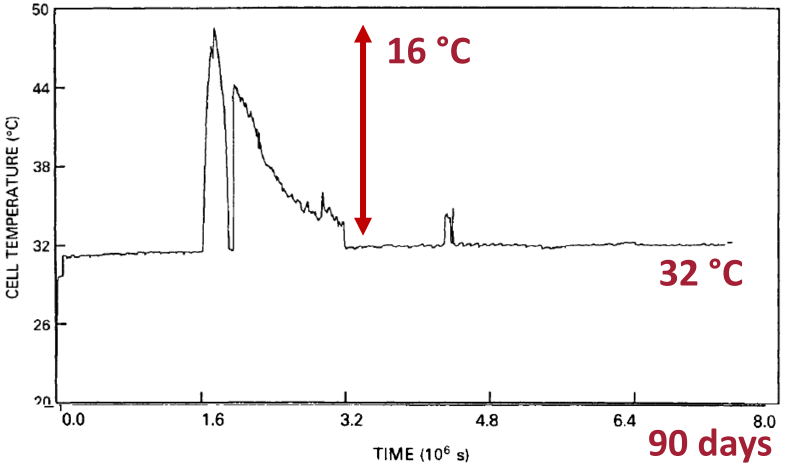
Example: Pd foil with electrochemical D loading



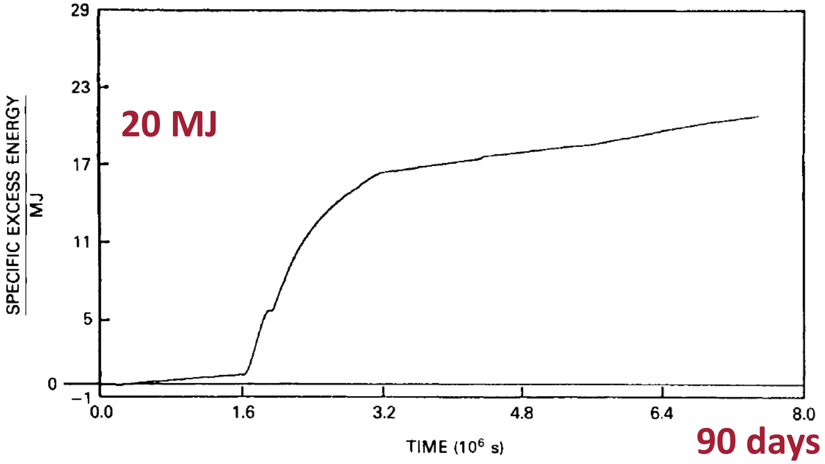
Experimental setup: Fleischmann-Pons cell



Calibration of the calorimeter through known power input



Unexplained temperature rises (excess heat)

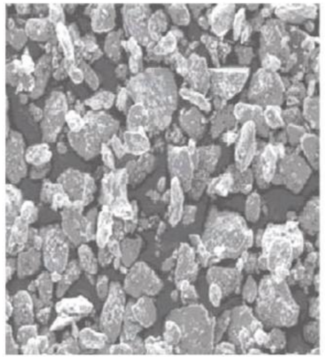


Excess energy (as accumulated excess power)

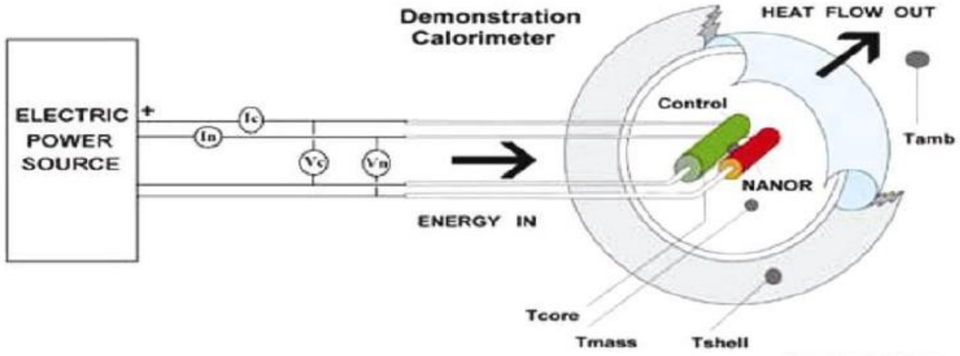
Pons, S., & Fleischmann, M. (1990). Calorimetric measurements of the palladium/deuterium system: Fact and fiction. Fusion Technology, 17, 669–679.

Characterization mode: heat

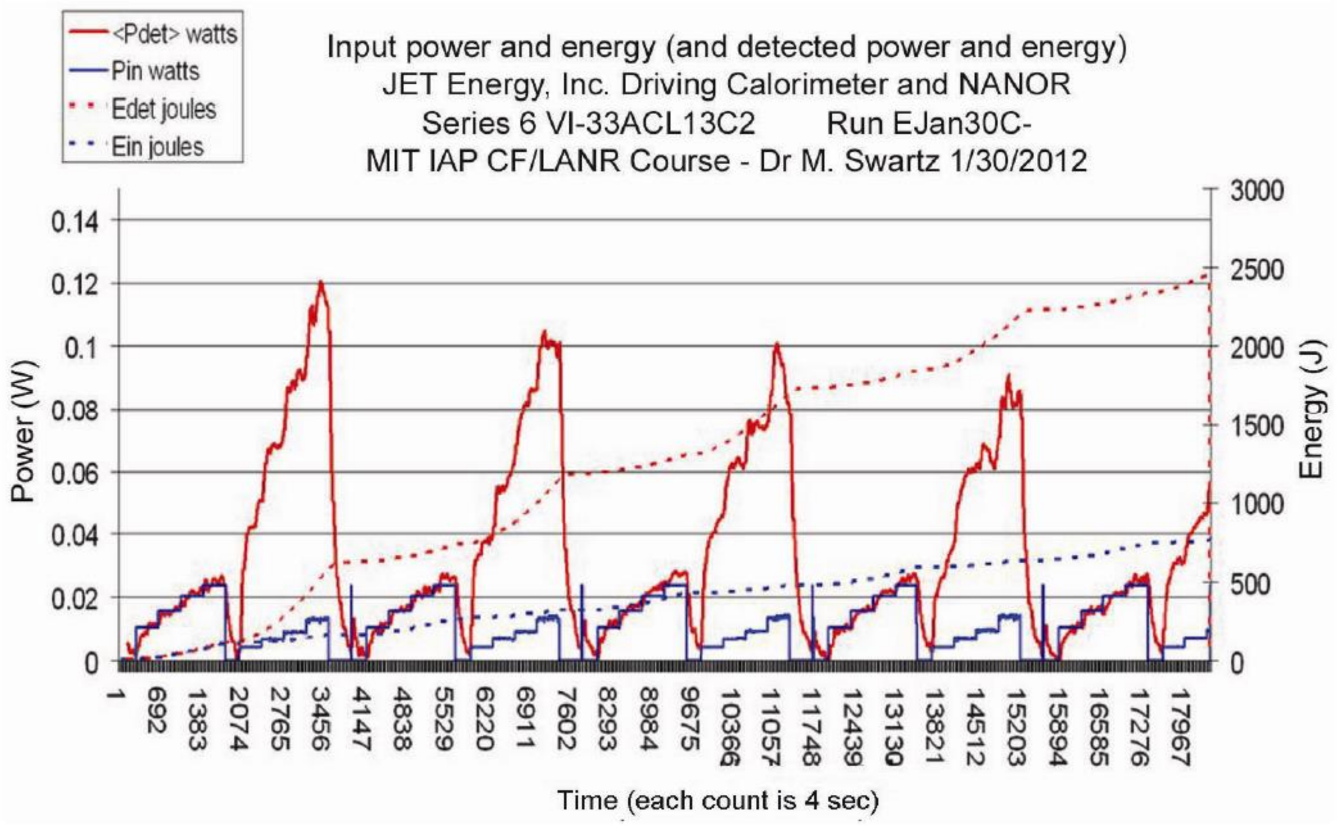
Example: PdD nanoparticles with electric discharge



PdD nanoparticles embedded in Zr pellets



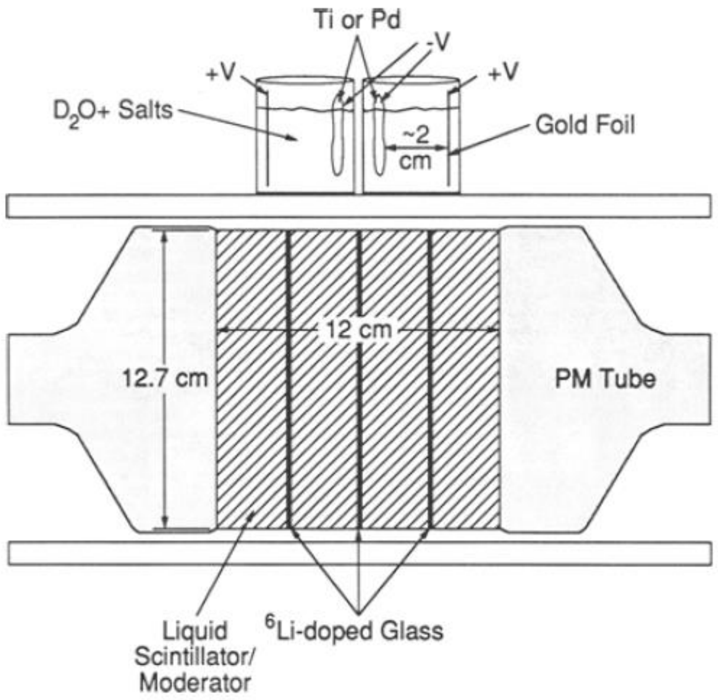
Calorimetry setup with resistive control



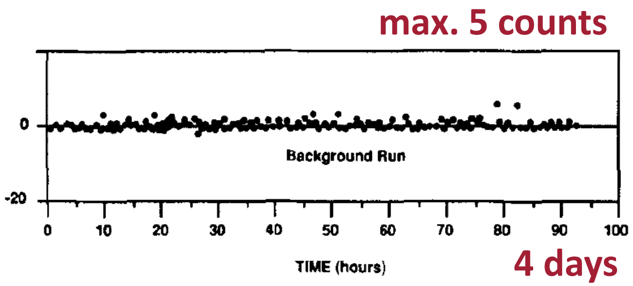
Reported excess power and accumulated excess energy

Swartz, M. R., et al (2015). Dry, preloaded NANOR®-type CF/LANR components. Current Science, 108, JSTOR.

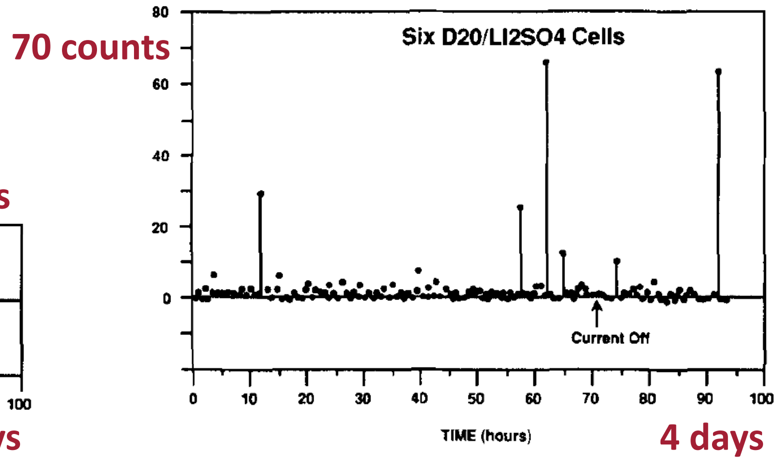
Example: Neutron emission from loaded Pd foil



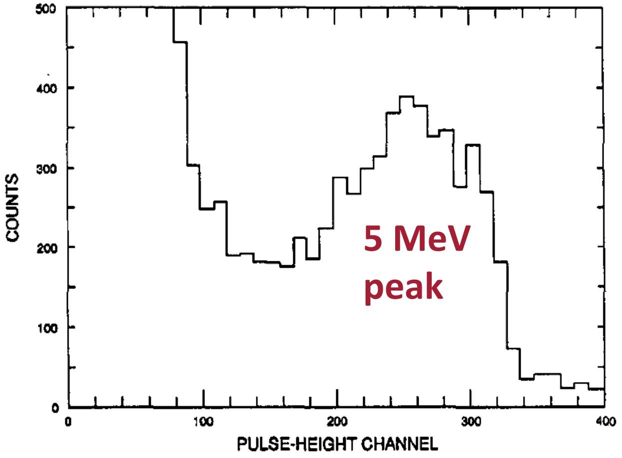
Experimental setup:
electrochemical cell above neutron spectrometer



Neutron counts during background run



Neutron counts during experimental run

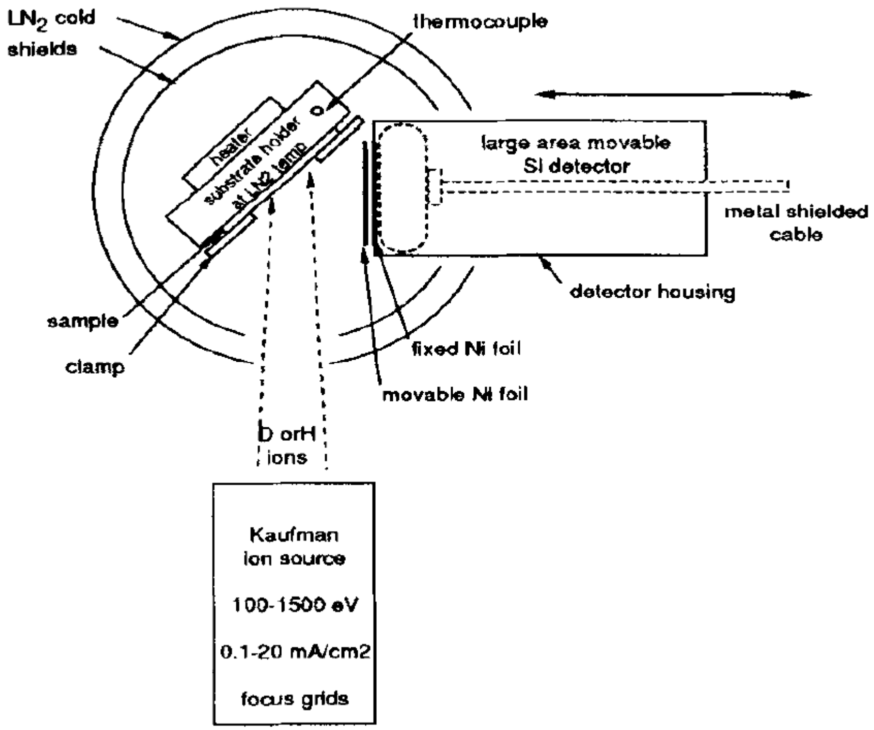


Neutron energy centers around 5 MeV

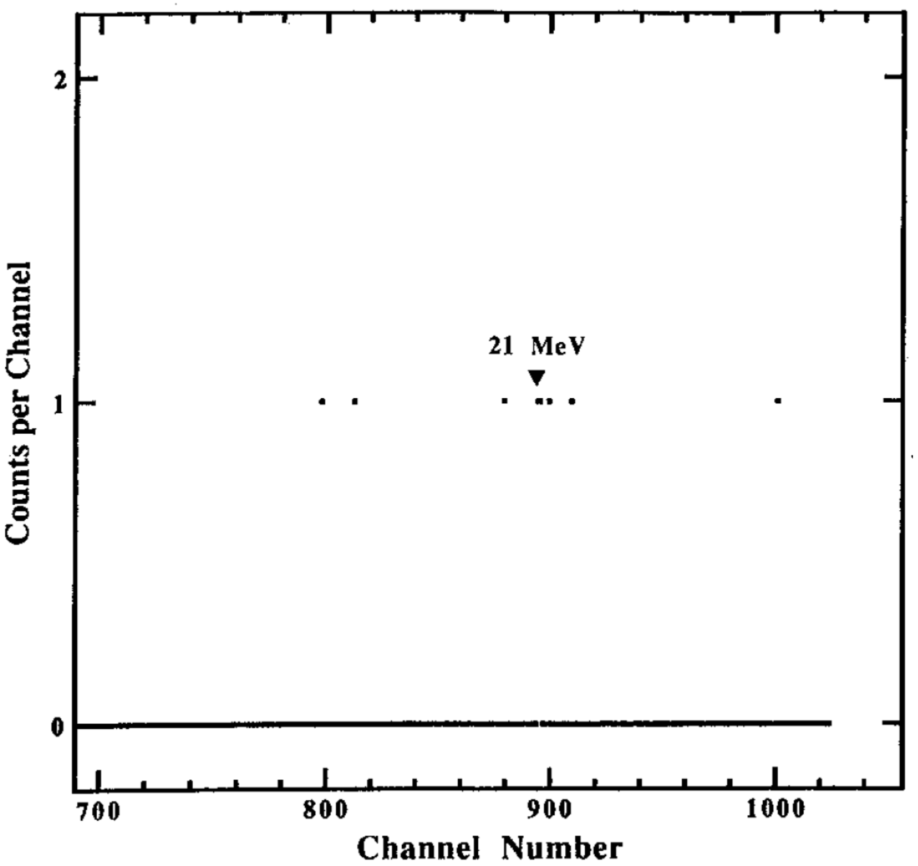
Jones, S. E., et al (1990). Anomalous nuclear reactions in condensed matter: Recent results and open questions. Journal of Fusion Energy, 9.

Characterization mode: energetic particles

Example: Charged particle emission from loaded Pd foil



Experimental setup:
vacuum chamber with low-energy deuteron beam on Pd foil target

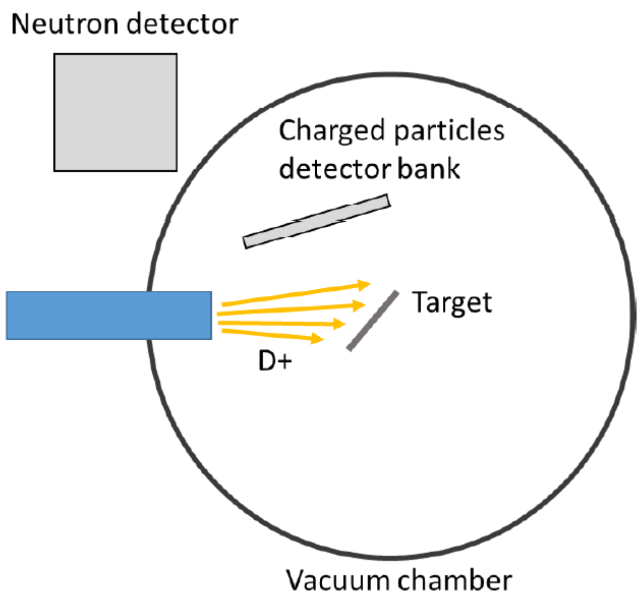


21 MeV charged particle counts from bombarded Pd foil

Chambers, G. P., Eridon, J. E., Grabowski, K. S., Sartwell, B. D., & Chrisey, D. B. (1990). Charged particle spectra of palladium thin films during low energy deuterium ion implantation. Journal of Fusion Energy, 9(3), 281–285.

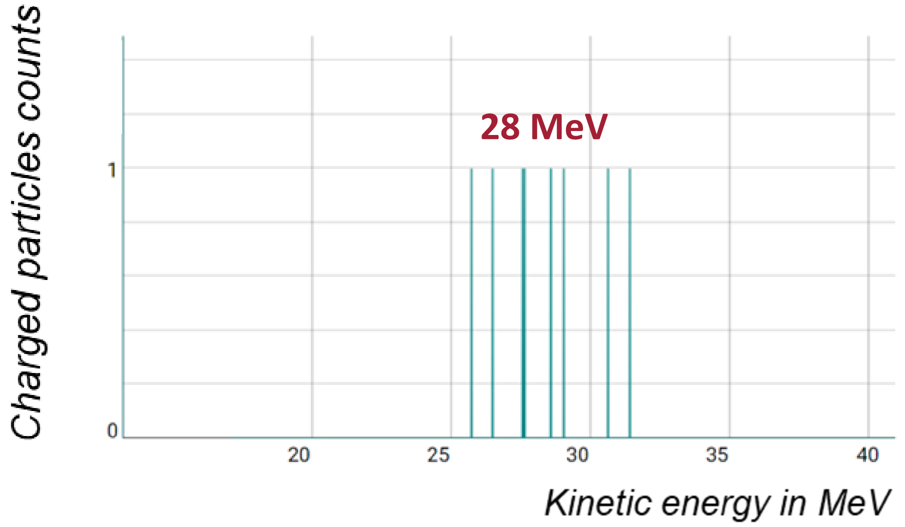
Characterization mode: energetic particles

Example: Charged particle emission from loaded Ti foil



Experimental setup:
vacuum chamber with low-energy deuteron beam on foil target

View of target sample during bombardment

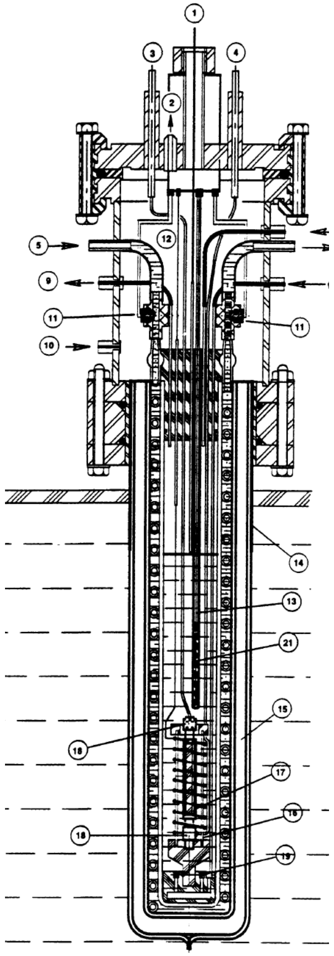


28 MeV charged particle counts from bombarded Ti foil

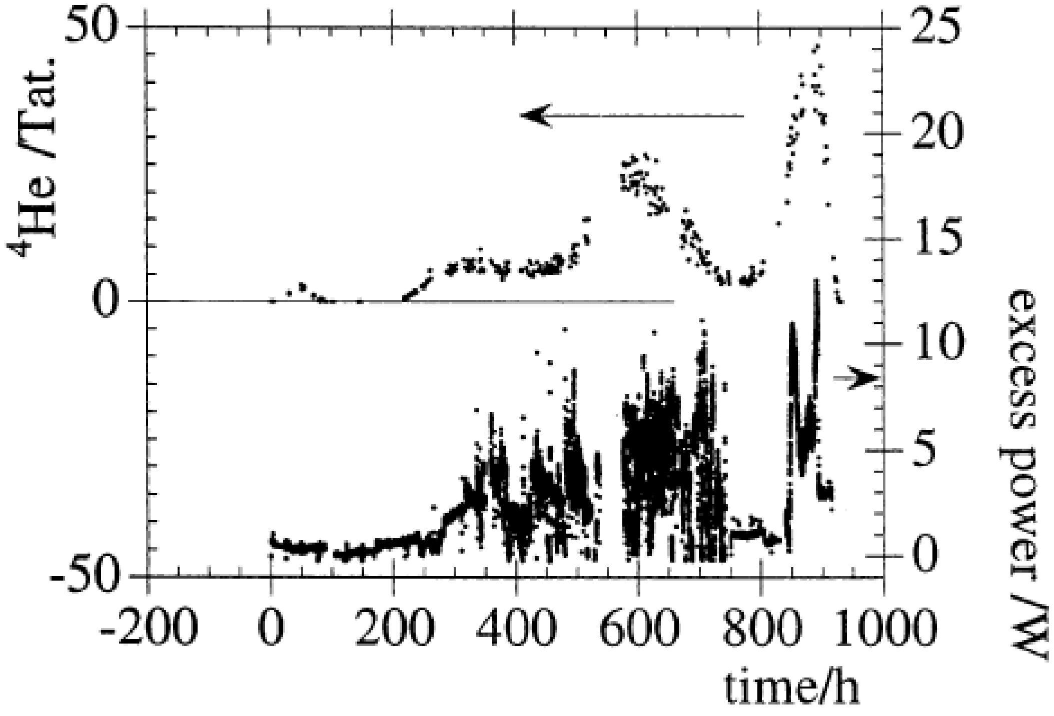
Forbes, S. (2019). Initial report on low-energy ion beam experiments with various metal targets [Conference Presentation]. ICCF22, Assisi, Italy.

Characterization mode: composition changes

Example: He-4 production from loaded Pd foil



Experimental setup: similarity to Fleischmann-Pons cell

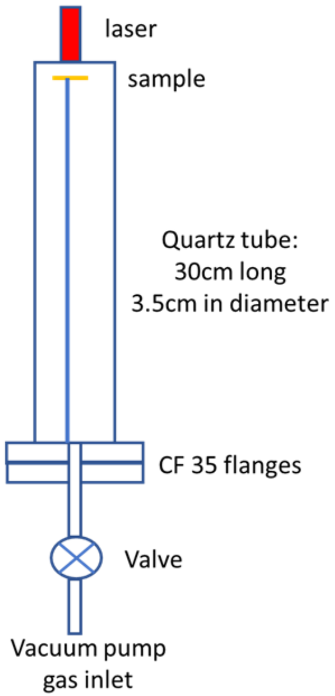


Measured He-4 (top) and excess heat (bottom) appearing correlated

Gozzi, D., et al (1998). X-ray, heat excess and 4He in the D/Pd system. J. Electroanal. Chem, 452.

Characterization mode: composition & morphology changes

Example: Possible fission products from gas loaded Pd



Scanning Electron Microscopy Image

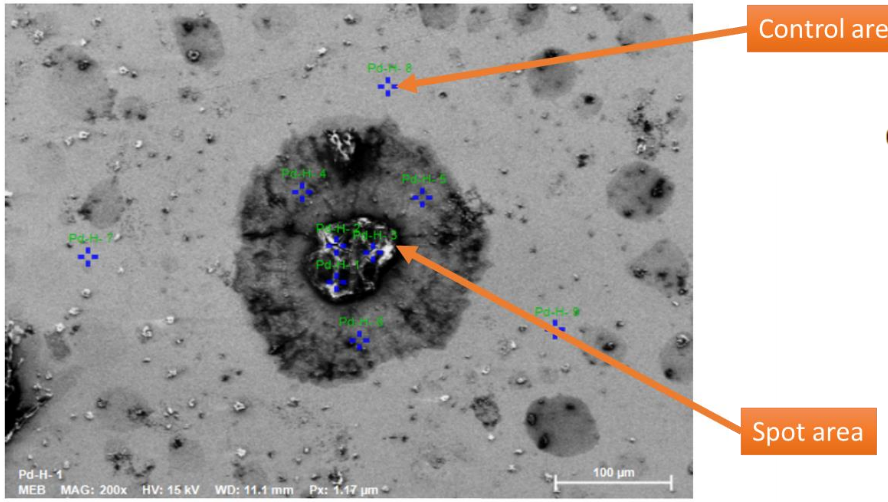
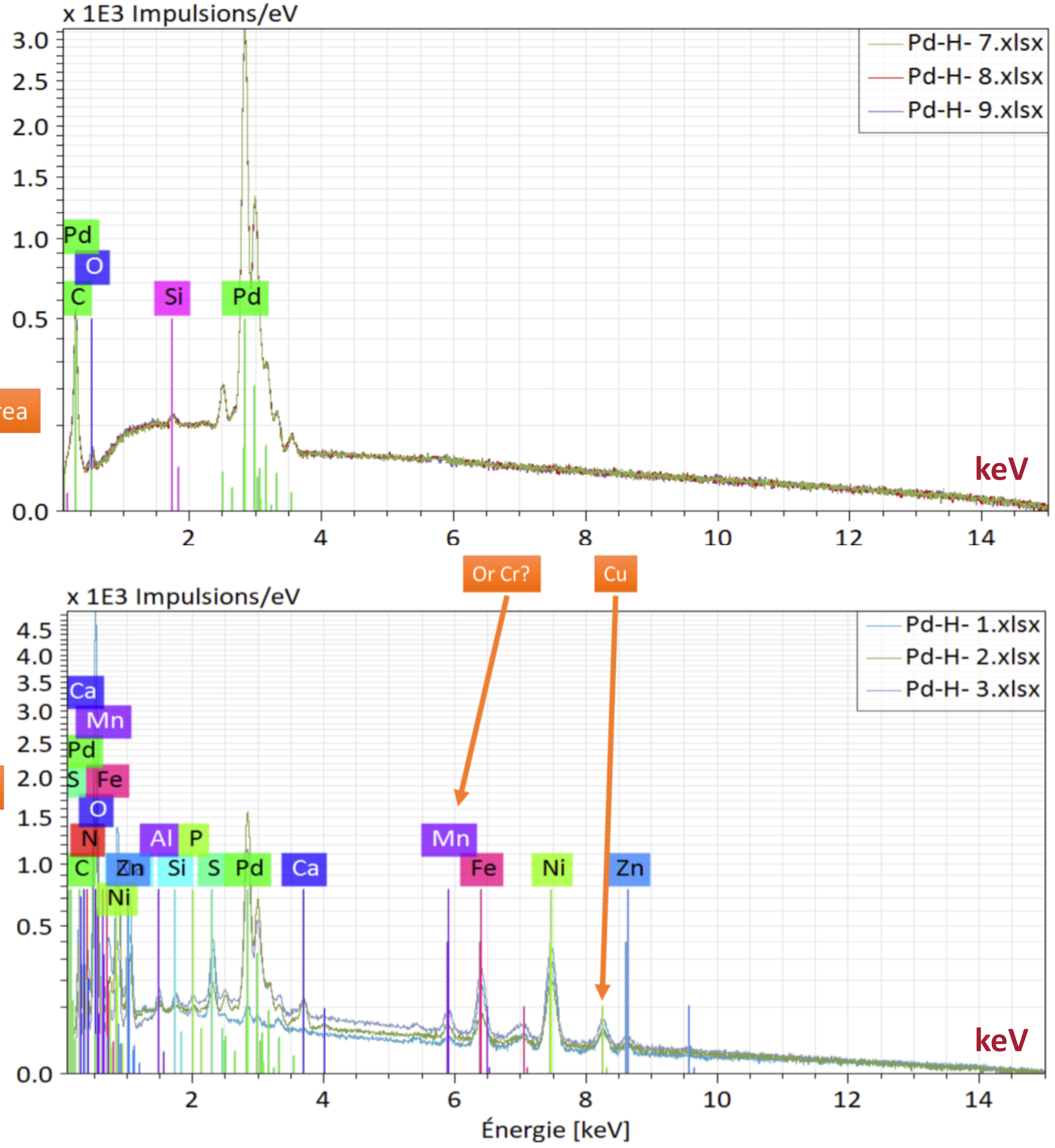


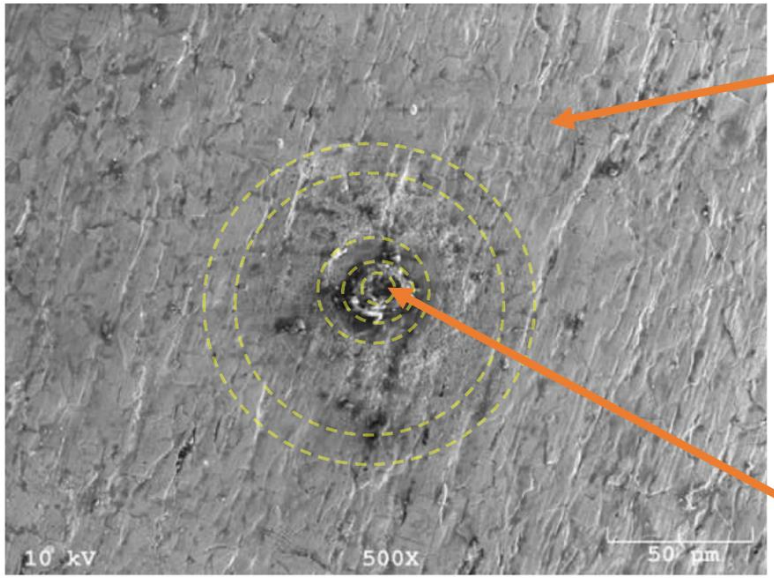
Image shows a hot spot: about 200um in diameter

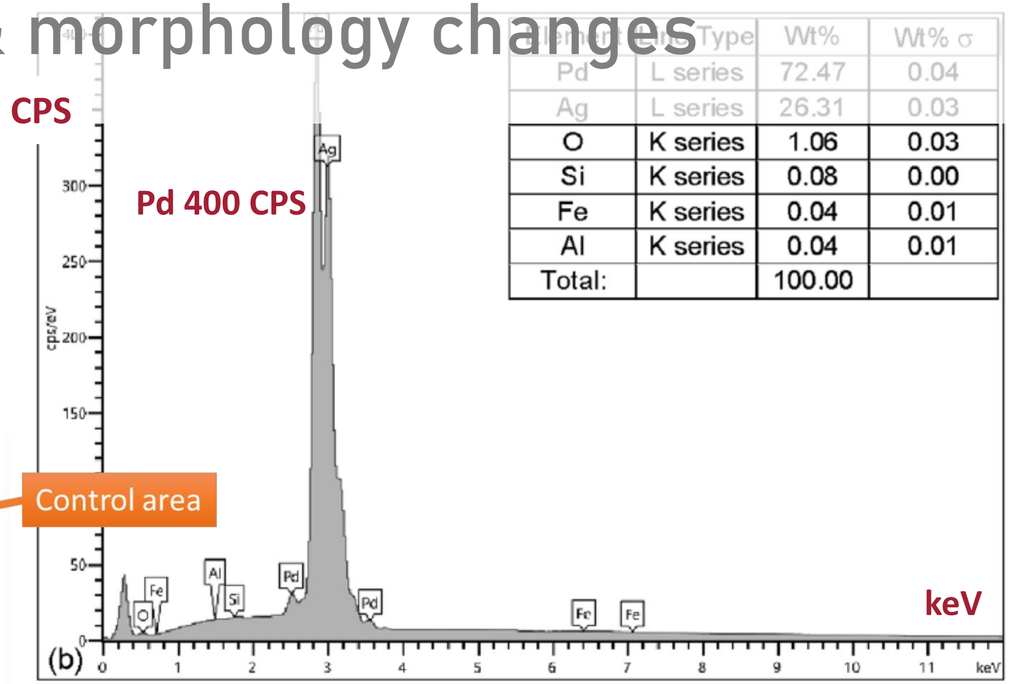


Biberian, J.-P. (2020, November 21). Transmutation induced by laser irradiation. RNBE 2020 Conference by French Society for Nuclear Science in Condensed Matter (SFSNMC), Paris.

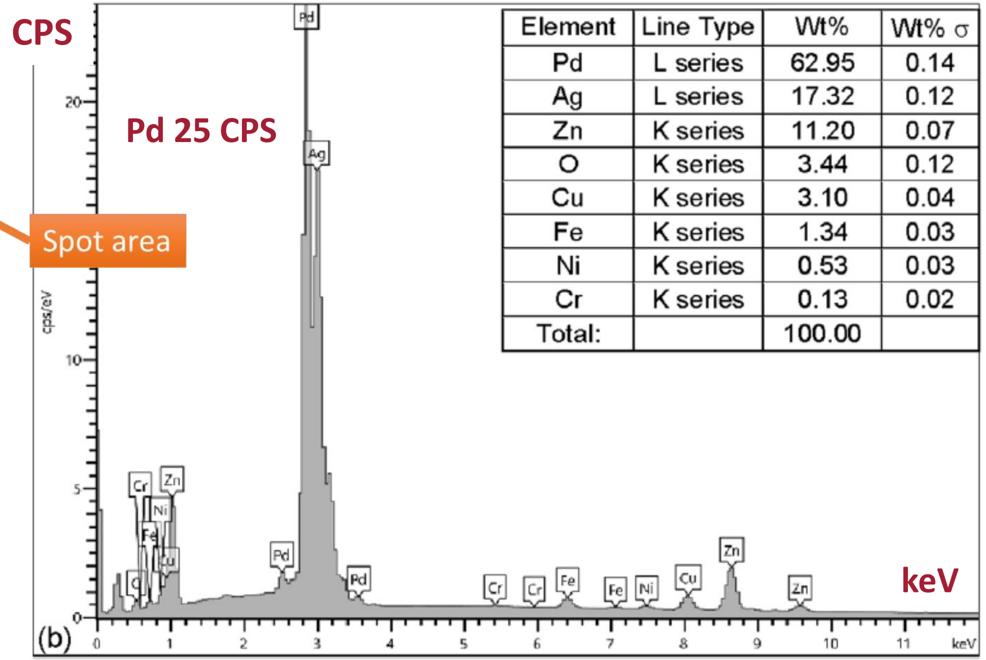
Characterization mode: composition & morphology changes

Example: Possible fission products from gas loaded Pd (2)





Element	Line Type	Wt%	Wt% σ
Pd	L series	72.47	0.04
Ag	L series	26.31	0.03
O	K series	1.06	0.03
Si	K series	0.08	0.00
Fe	K series	0.04	0.01
Al	K series	0.04	0.01
Total:		100.00	



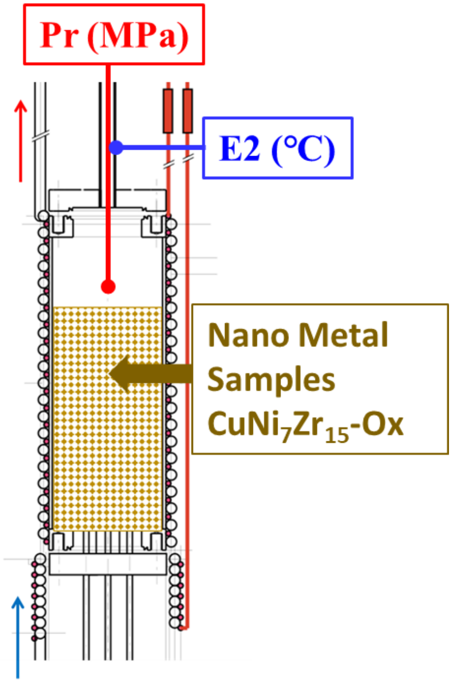
Element	Line Type	Wt%	Wt% σ
Pd	L series	62.95	0.14
Ag	L series	17.32	0.12
Zn	K series	11.20	0.07
O	K series	3.44	0.12
Cu	K series	3.10	0.04
Fe	K series	1.34	0.03
Ni	K series	0.53	0.03
Cr	K series	0.13	0.02
Total:		100.00	

Fralick, G. C., Hendricks, R. C., Jennings, W. D., Benyo, T. L., VanKeuls, F. W., Ellis, D. L., Steinetz, B. M., Forsley, L. P., & Sandifer, C. E. (2020). Transmutations observed from pressure cycling palladium silver metals with deuterium gas. International Journal of Hydrogen Energy, 45(56), 32320–32330.

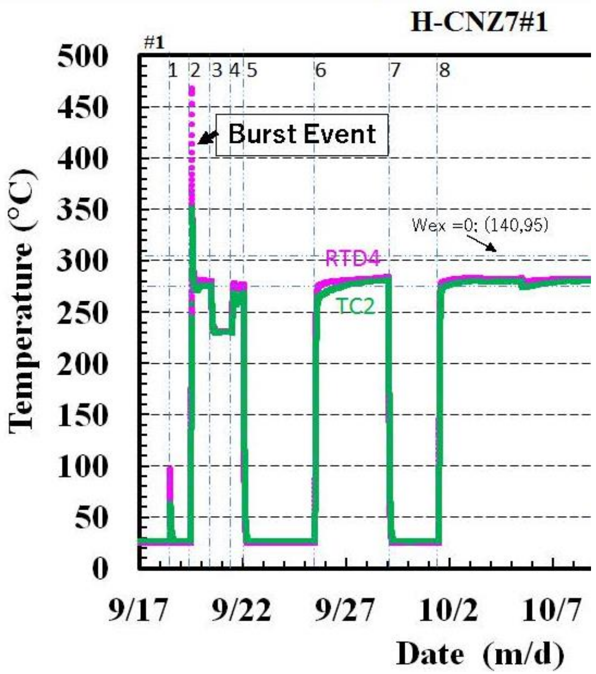
Characterization mode: morphology changes

Example: Gas loaded CuNi nanoparticles with moderate heating

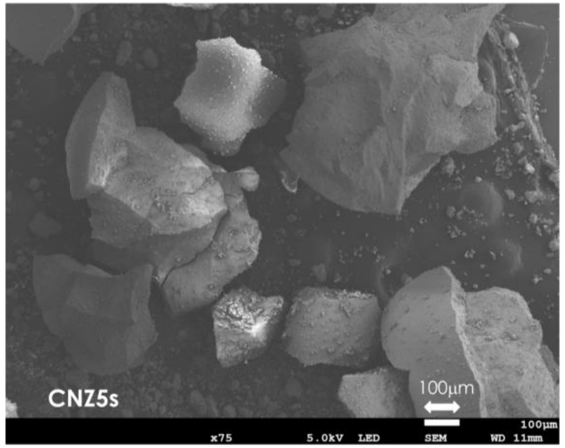
CuNi nanoparticles embedded in Zr pellets



Reactor chamber and calorimetry setup



Temperature burst during initial heating



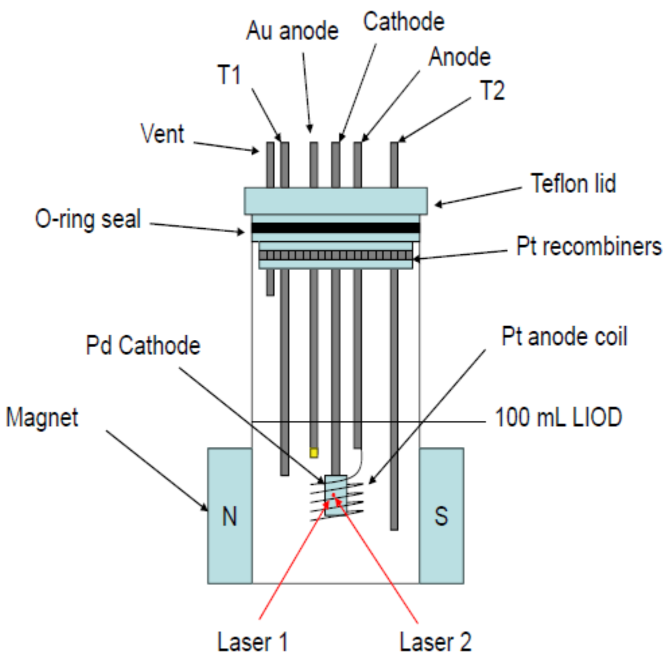
SEM image of cracked Zr pellets

Iwamura, Y. et al. (2019). Recent Advances in Heat Generation Experiments using Nano-sized Metal Composite and Hydrogen Gas at Condensed Matter Nuclear Reaction Division of Tohoku University. Conference Presentation presented at the LANR/CF Colloquium, MIT.

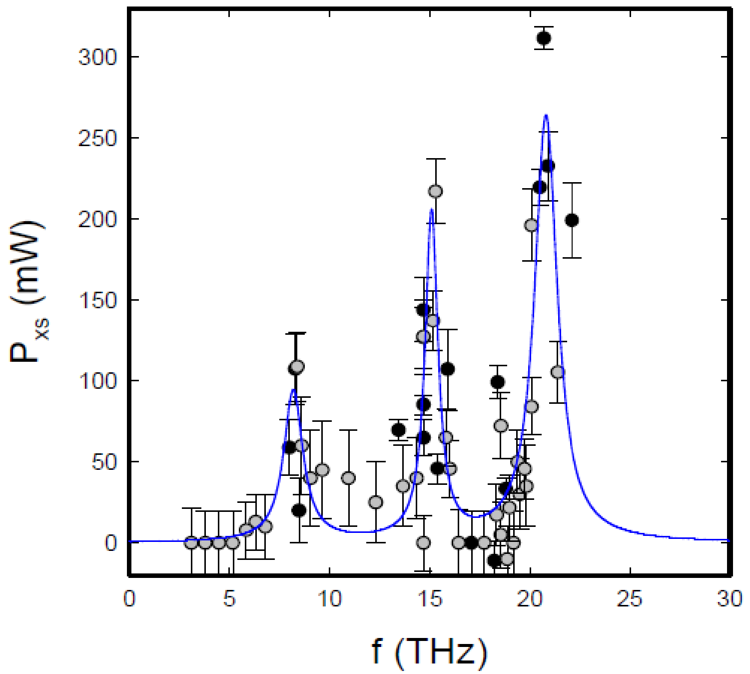
Characterization mode: lattice dynamics

Example: Excess heat as a function of stimulation frequency

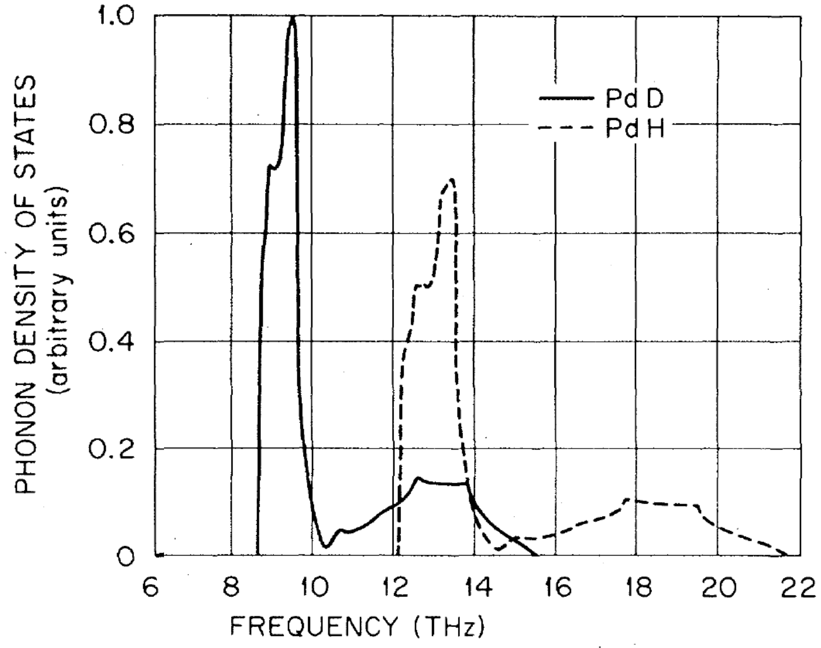
From non-LENR literature:



Experimental setup: electrolysis with Pd cathode



Excess heat from dozens of experiments as a function of stimulation frequency



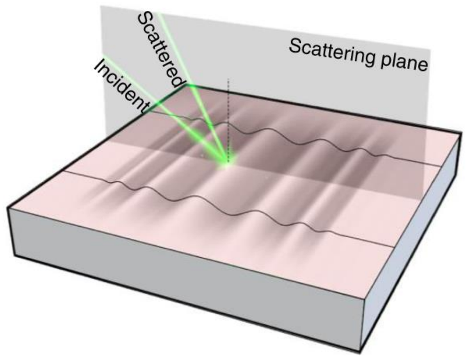
Vibrational modes of a Pd lattice with high D and H loading

Hagelstein, P. L., et al (2010). Terahertz difference frequency response of pdd in two-laser experiments. MIT Dspace. https://dspace.mit.edu/handle/1721.1/71612
Rowe, J. M., et al (1974). Lattice Dynamics of a Single Crystal of Pd D 0.63. Physical Review Letters, 33, 1297.

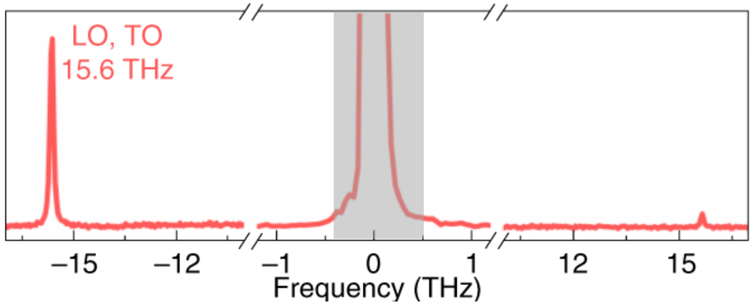
Characterization mode: lattice dynamics

Example: Raman peaks correlated with excess heat

From non-LENR literature:

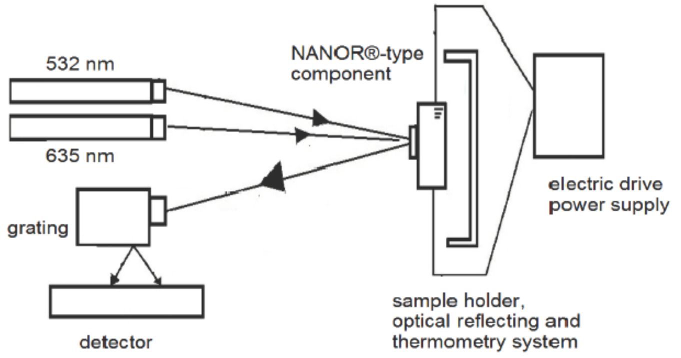


Principle of Raman spectroscopy

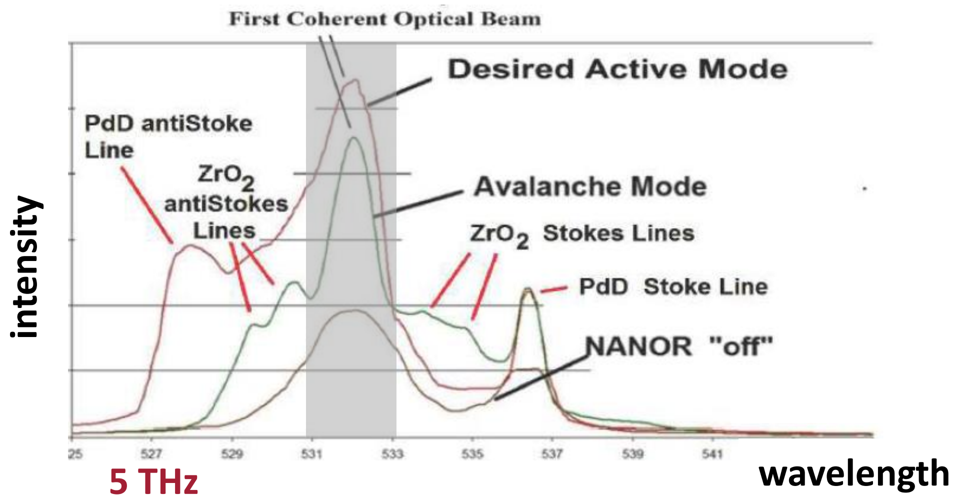


Vibrational peak for Si sample

LENR literature:



Experimental setup: Pd nanoparticles sample (akin to Swartz et al. 2015 above) with Raman measurement



PdD Raman peaks are low before and after excess heat production (brown and green) but high during excess heat production (red)

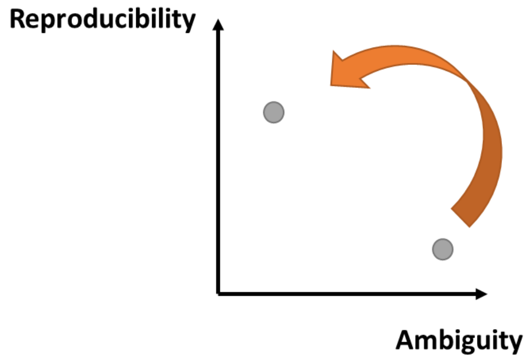
Swartz, M. R., & Hagelstein, P. L. (2017). Increased PdD anti-Stokes Peaks are Correlated with Excess Heat Mode. J. Condensed Matter Nucl. Sci, 24, 130–145.

What can we learn from reviewing the LENR literature from this perspective?

Two main lessons

Lesson I: relevant to the **ambiguity challenge**

Lesson II: relevant to the **reproducibility challenge**



Lesson I: relevant to the ambiguity challenge

HEAT

ENERGETIC PARTICLES

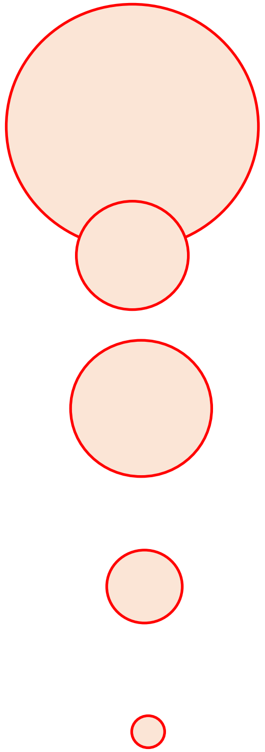
LATTICE COMPOSITION + CHANGES

LATTICE MORPHOLOGY + CHANGES

LATTICE DYNAMICS + CHANGES

Alternative explanations:

Number of experiments:



Lesson I: relevant to the ambiguity challenge

Alternative explanations:

Number of experiments:

HEAT

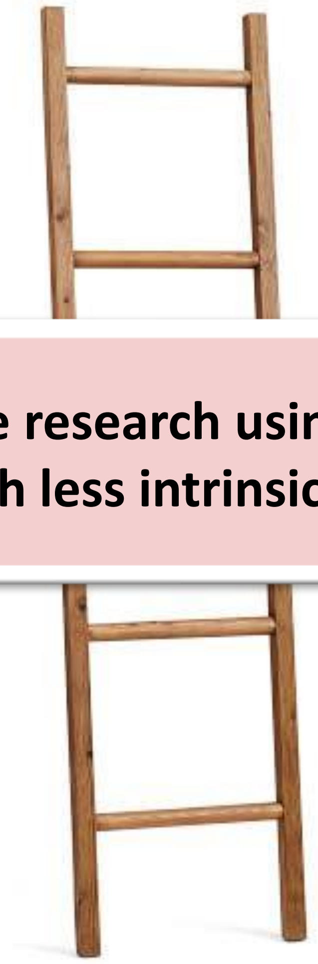
ENERGETIC PARTICLES

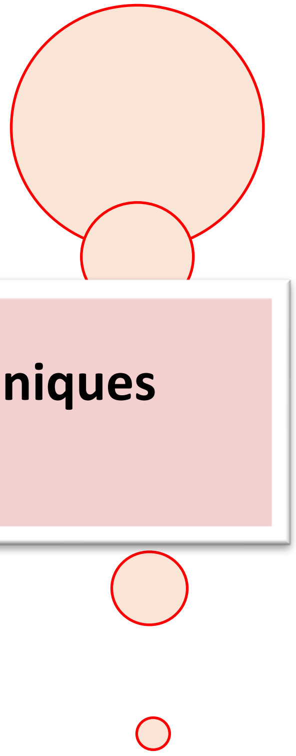
LATTICE C

Need to conduct more research using characterization techniques with less intrinsic ambiguity.

LATTICE MORPHOLOGY + CHANGES

LATTICE DYNAMICS + CHANGES





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ENERGETIC PARTICLES	?	?	5 MeV neutrons	21 MeV charged particles	28 MeV charged particles	X-ray film exposure, ?	?	?	?	?	?
LATTICE COMPOSITION	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Pd, D, P, ?	Ti, D, P, ?	Pd, D, P, ?	Pd, Si, D, P, ?	Pd, Ag, Fe, Si, Al, D, P, ?	Pd, Ni, Zr, D, P, ?	Pd, D, P, ?	Pd, Zr, D, P, ?
+ CHANGES	?	?	?	?	?	He-4 production	Fe, Ni, Cu, Zn, Mn/Cr production	Fe, Ni, Cu, Zn, Cr production	?	?	?
LATTICE MORPHOLOGY	?	?	?	?	?	?	?	?	?	?	?
+ CHANGES	?	?	?	?	?	?	Spot formation	Spot formation	Cracks	?	?
LATTICE DYNAMICS	Uncontrolled hydrogen diffusion	Uncontrolled electric discharge	Uncontrolled hydrogen diffusion	~100 eV bombard-ment	~100 eV bombard-ment	Uncontrolled Hydrogen diffusion	Optical laser irradiation	Uncontrolled hydrogen diffusion	Uncontrolled hydrogen diffusion	Controlled THz photon stimulation	Uncontrolled electric discharge
+ CHANGES	?	?	?	?	?	?	?	?	?	?	5 THz PdD Raman peaks

	Fleischmann & Pons 1990	Swartz 2015	Jones et al. 1990	Chambers et al. 1990	Forbes et al. 2019	Gozzi et al. 1998	Biberian 2020	Fralick et al. 2020	Kitamura et al. 2018	Letts et al. 2010	Swartz et al. 2017
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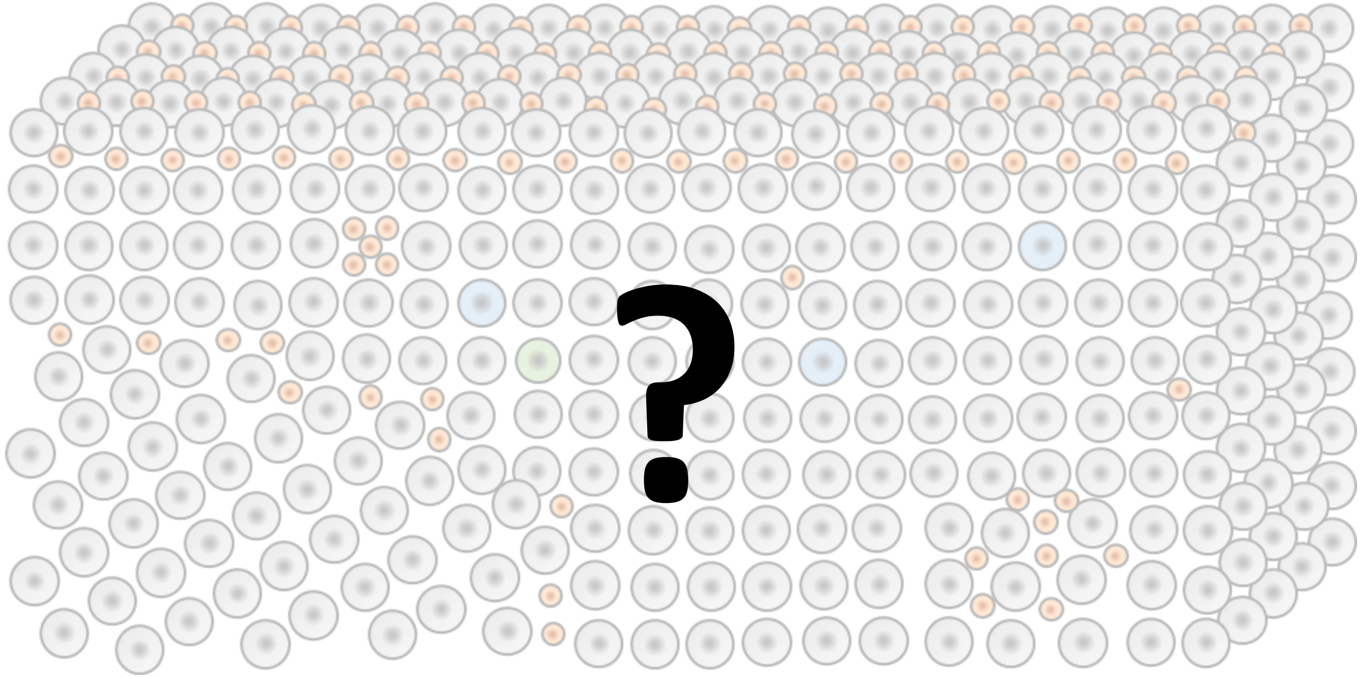
+ CHANGES	?	?	?	?	?	?	?	?	?	?	5 THz PdD Raman peaks

Lesson II: relevant to the reproducibility challenge

Too many question marks

Too many uncontrolled/uncharacterized variables



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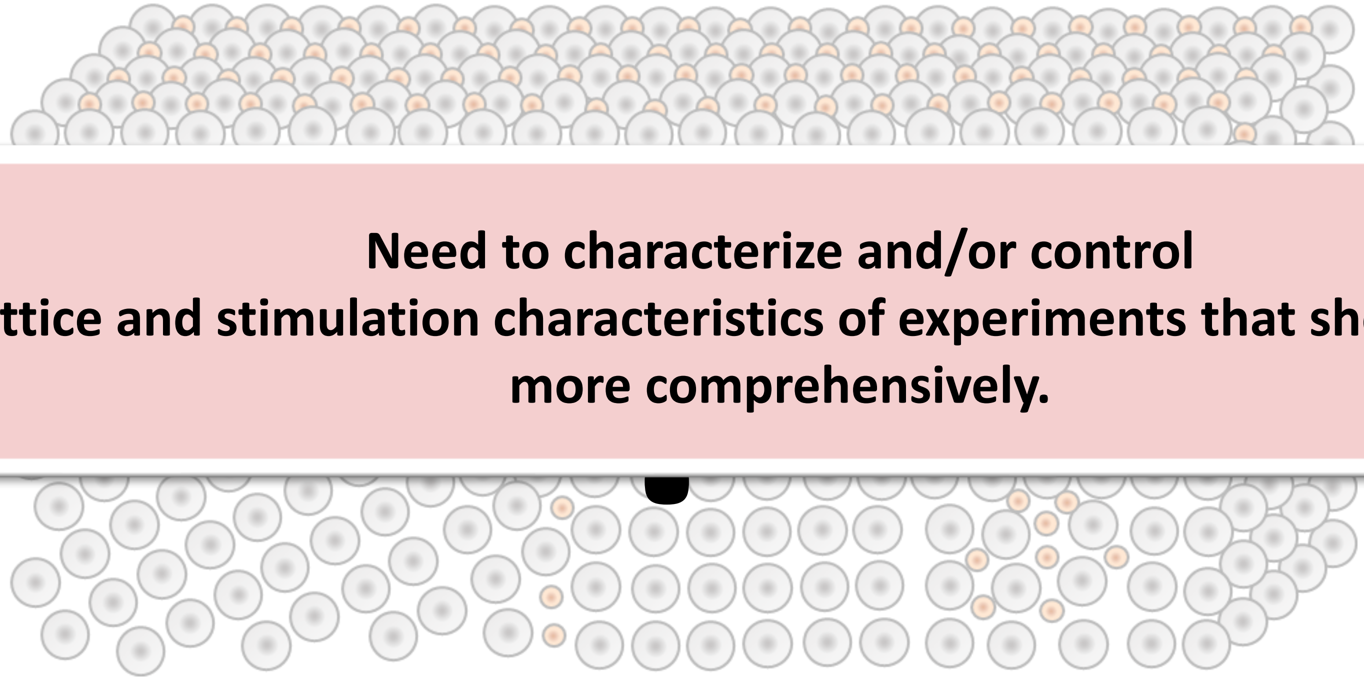

Need to characterize and/or control
lattice and stimulation characteristics of experiments that show effects more comprehensively.

C. Implications for future research

What do these lessons mean for future research?

We propose a two-pronged approach to respond to these lessons and to address the ambiguity challenge and the reproducibility challenge.

Implications

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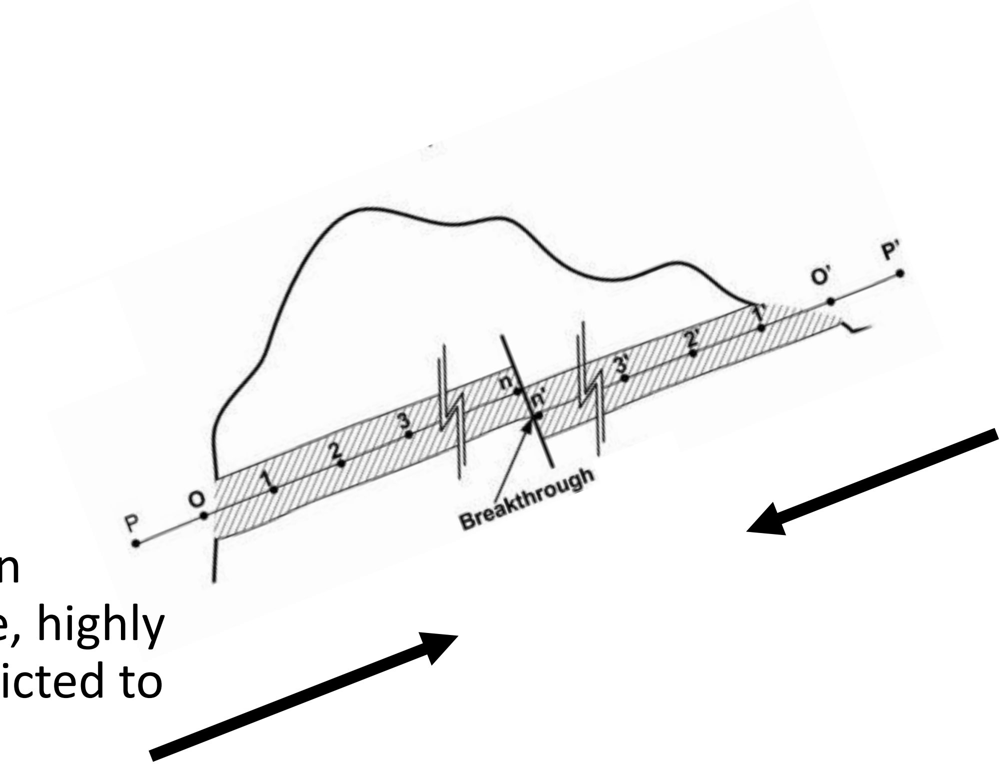

Top-down:
Focus on a small number of experiments and conduct comprehensive characterizations.

Bottom-up:
Design hypothesis-driven experiments with simple, highly controlled samples predicted to exhibit LENR effects.

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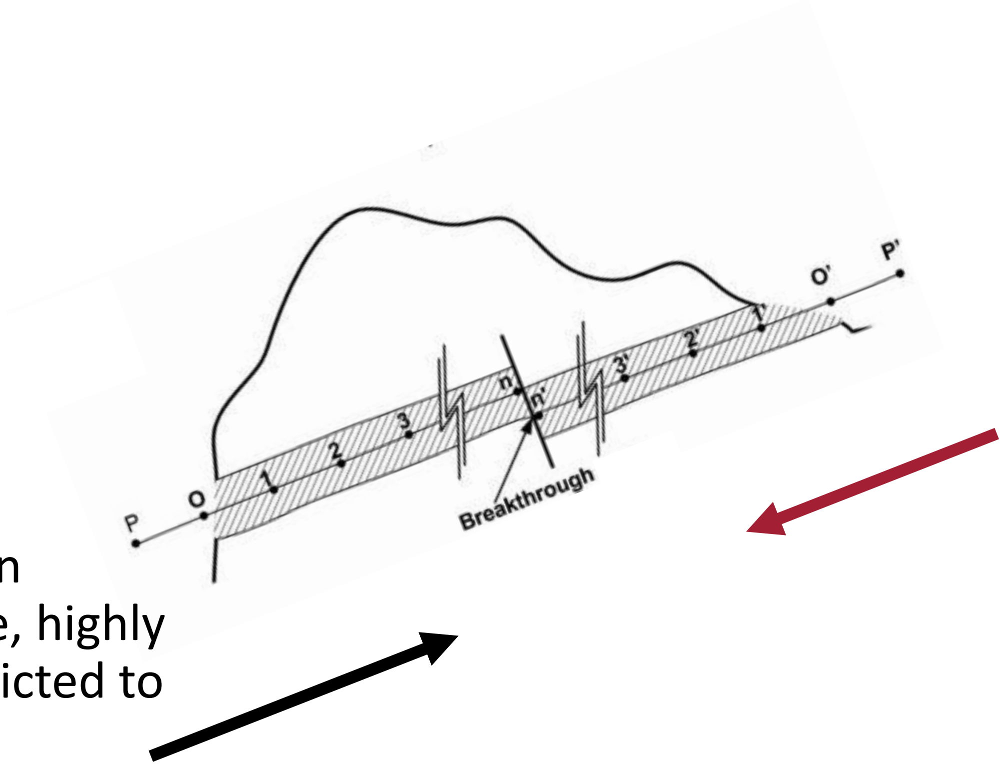

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+ CHANGES	?	?	?	?	?	He-4 production	Fe, Ni, Cu, Zn, Mn/Cr production	Fe, Ni, Cu, Zn, Cr production	?	?	?
LATTICE MORPHOLOGY	?	?	?	?	?	?	?	?	?	?	?
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LATTICE MORPHOLOGY	?	?	?	?	?	?	?	?	?	?	?
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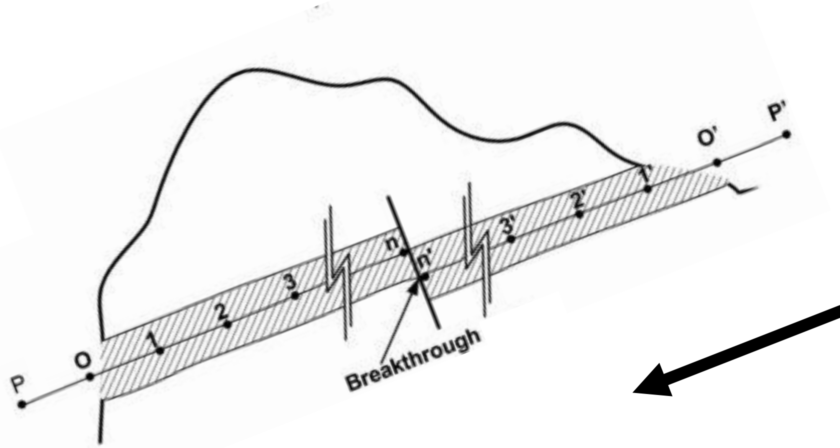


Top-down:
Focus on a small number of experiments and conduct comprehensive characterizations.

Bottom-up:
Design hypothesis-driven experiments with simple, highly controlled samples predicted to exhibit LENR effects.

Bottom-up approach

Thinking about mechanisms

What is known and accepted in the wider literature about enhancing nuclear transitions:

- Atomic physics
  - Electrons can increase proximity between nuclei.
  - Vacancies allow for both close proximity and high electron density in the lattice.

Want lattice with high screening and close proximity

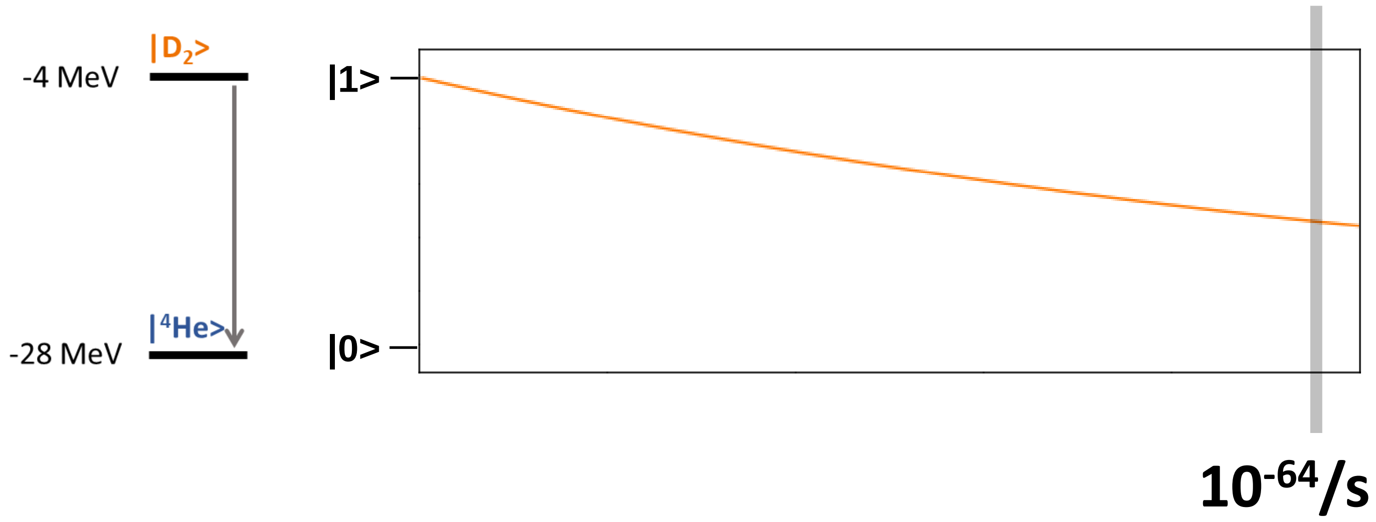
- Quantum dynamics:
  - Photons, phonons, plasmons, etc. can cause couplings between nuclei.
  - Couplings can intensify with coherence.
  - Strong couplings can change state transition and reaction parameters.

Want to externally induce weak couplings and enhance via superradiance

Prados-Estévez, F. M., Subashiev, A. V., & Nee, H. H. (2017). Strong screening by lattice confinement and resultant fusion reaction rates in fcc metals. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 407, 67–72.
Terhune, J. H., & Baldwin, G. C. (1965). Nuclear Superradiance in Solids. Physical Review Letters, 14(15), 589–591.

Combining screening and transition rate enhancement

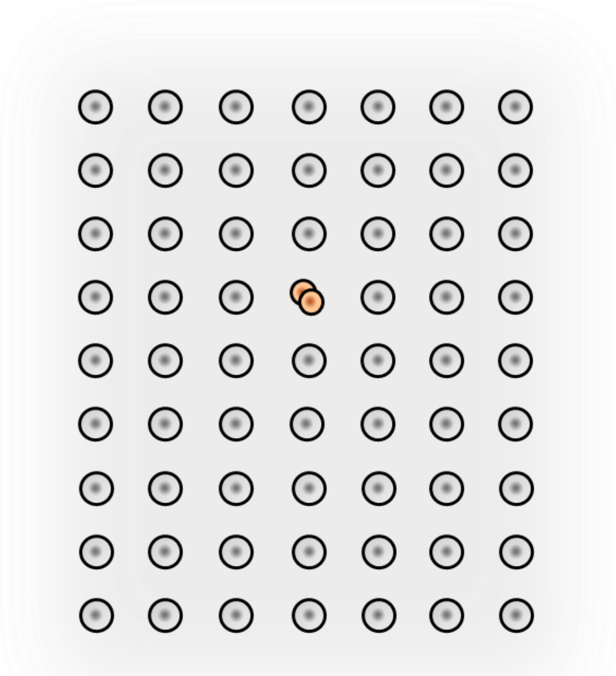
Start with an isolated D pair

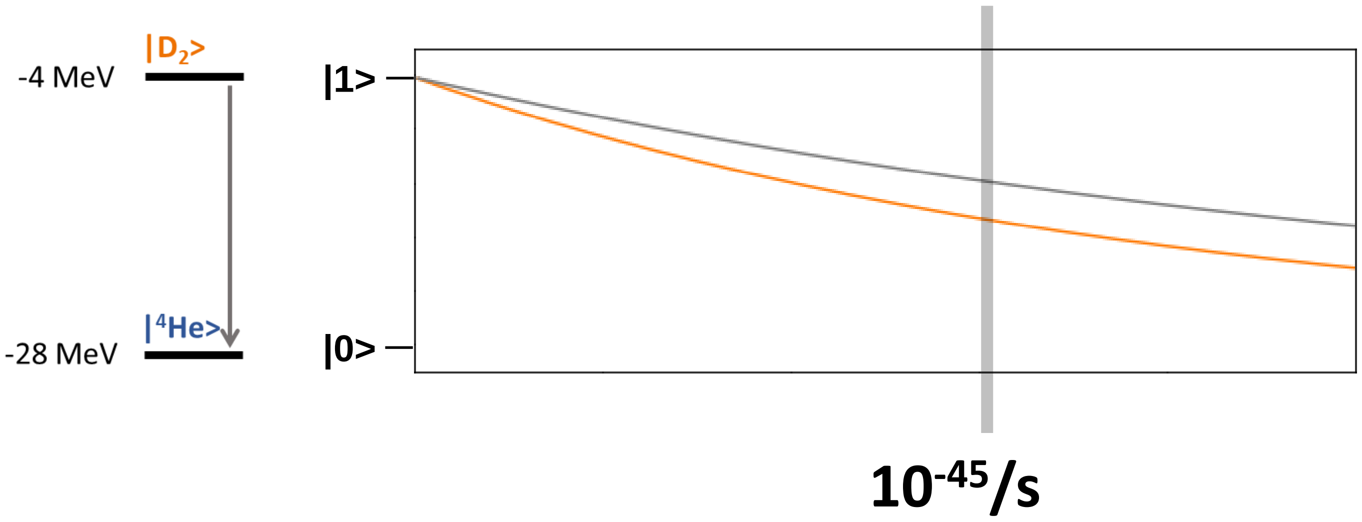


Koonin, S. E., & Nauenberg, M. (1989). Calculated fusion rates in isotopic hydrogen molecules. Nature, 339(6227), 690.

Combining screening and transition rate enhancement

Place D pair in a vacancy of a Pd lattice



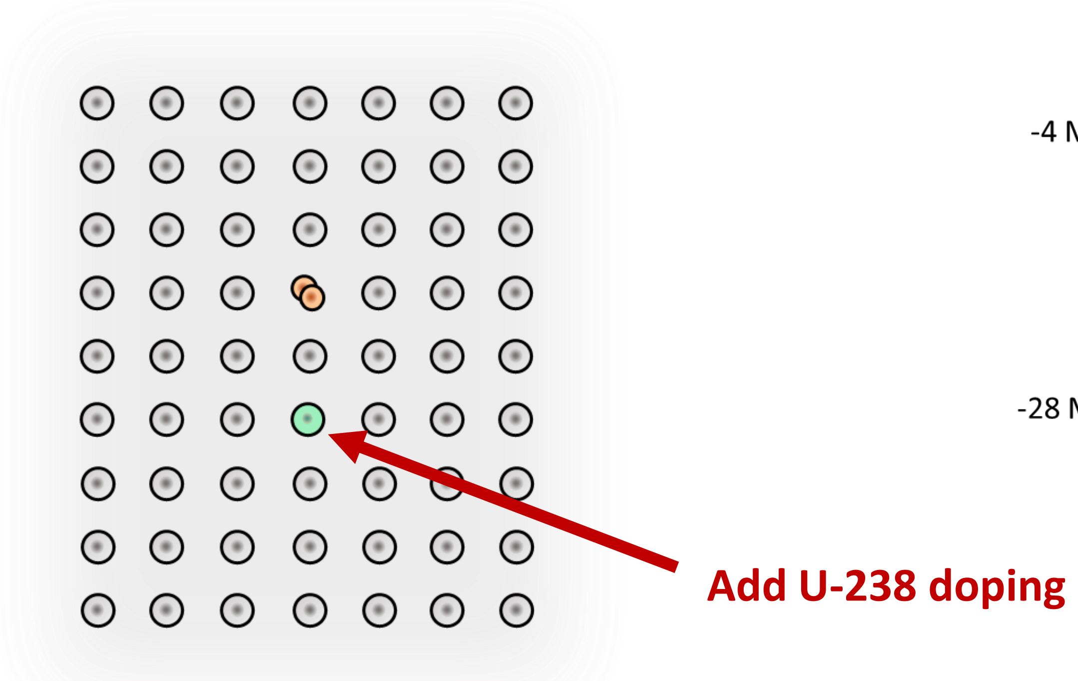


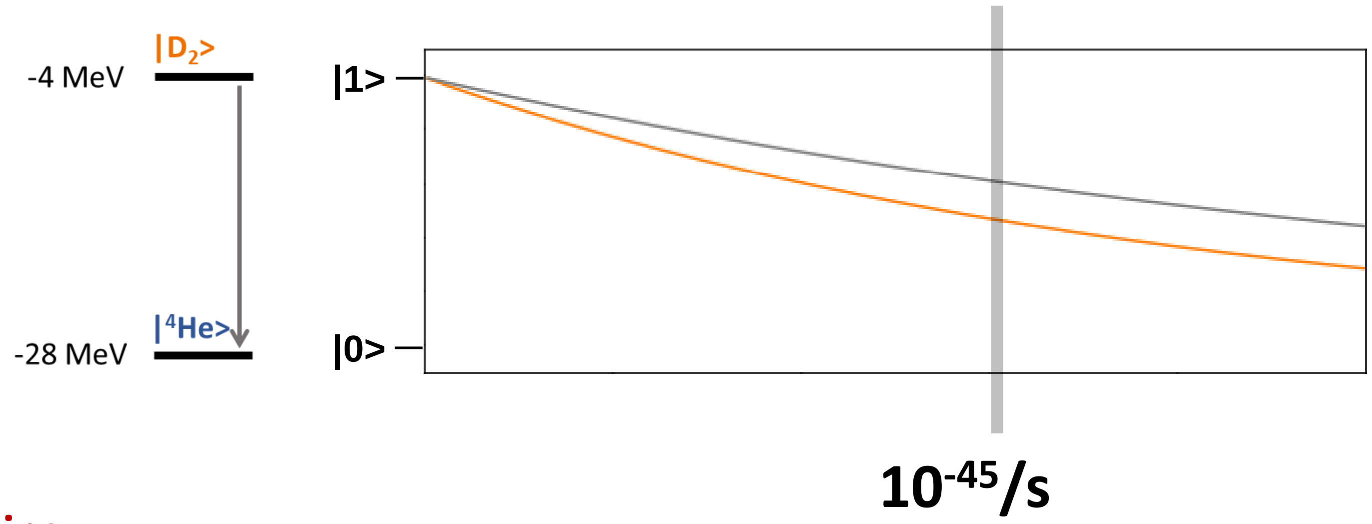
Doped Pd lattice with vacancy hydrogen clusters:
DD distance <100 pm
Screening potential > 150 eV

Targosz-Ślęczka, N., Czerski, K., Huke, A., Ruprecht, G., Weissbach, D., Martin, L., Kaczmarski, M., & Winter, H. (2013). Experiments on screening effect in deuteron fusion reactions at extremely low energies. The European Physical Journal Special Topics, 222(9), 2353–2359.

Combining screening and transition rate enhancement

Add resonant receiver nuclei as dopants





Doped Pd lattice with vacancy hydrogen clusters:
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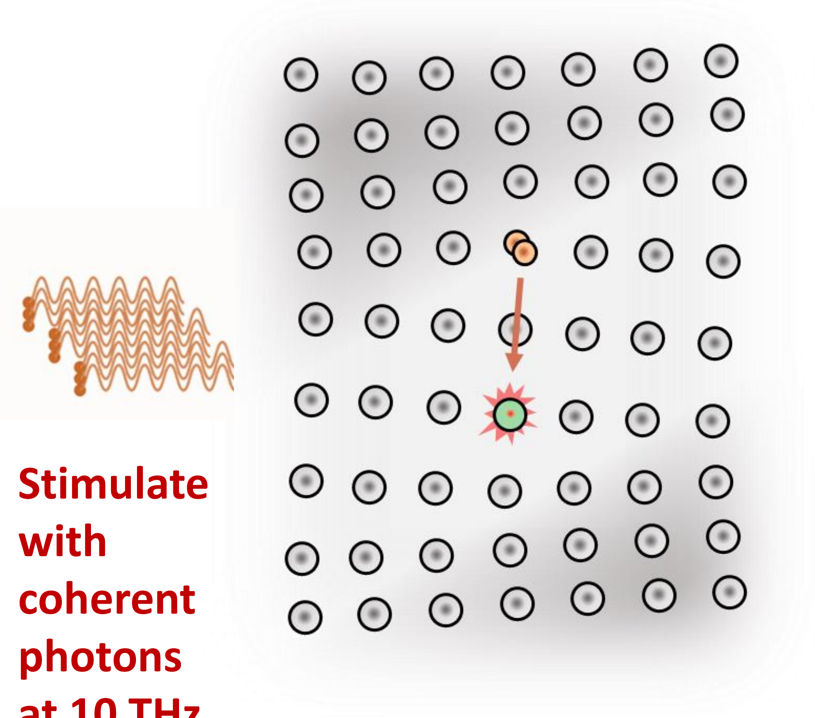
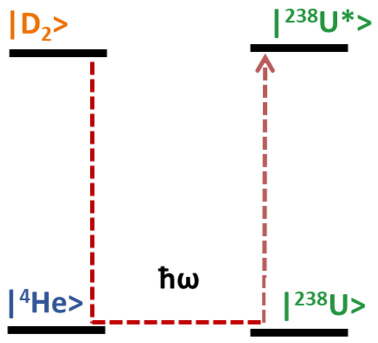
Screening potential > 150 eV

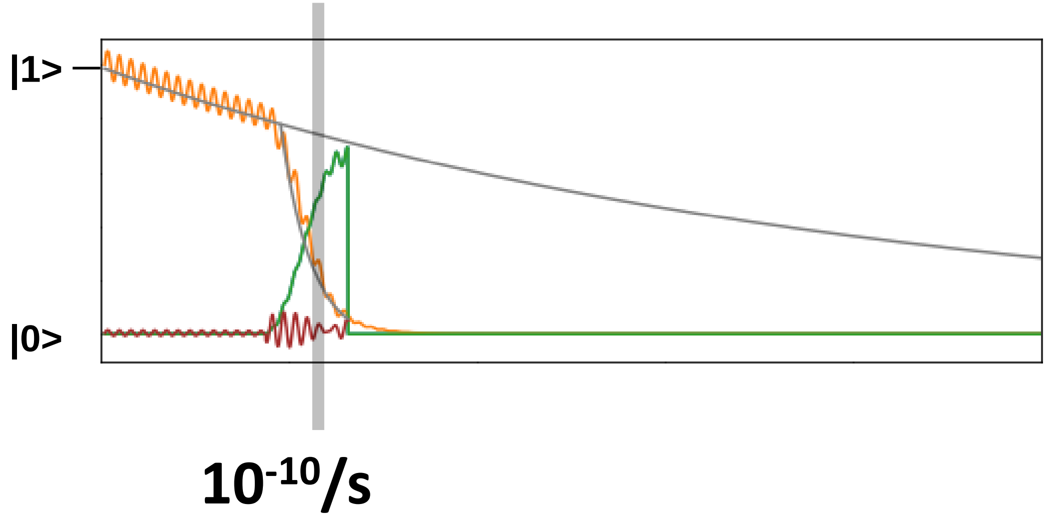
Combining screening and transition rate enhancement

Enhance couplings between nuclei via coherent stimulation



Stimulate with coherent photons at 10 THz

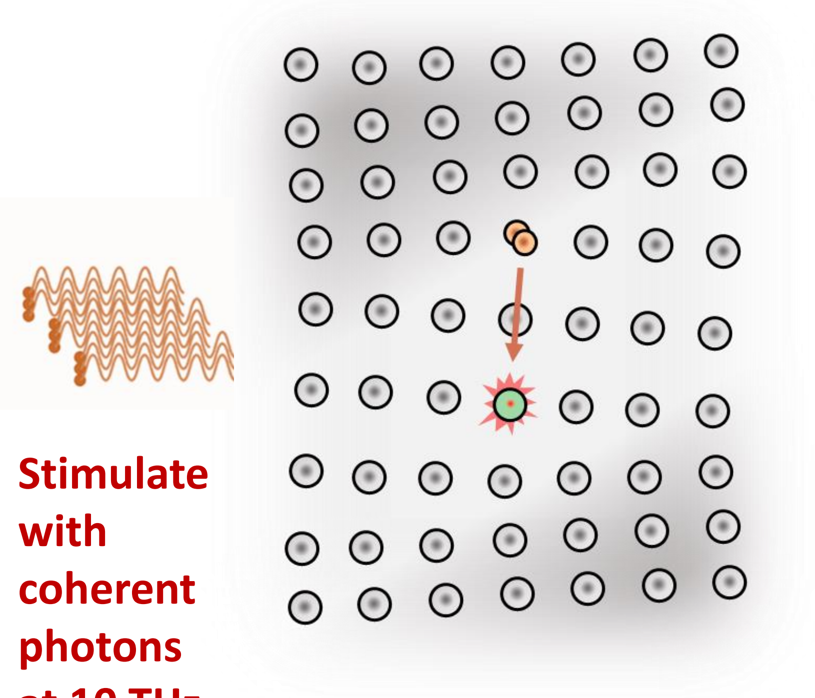




Hagelstein, P. L. (2020). Models based on phonon-nuclear coupling. In Cold Fusion (pp. 283–300). Elsevier.
Hagelstein, P. L. (2018). Phonon-mediated Nuclear Excitation Transfer. J. Cond. Mat. Nucl. Sci, 27, 97–142.

Combining screening and transition rate enhancement

Enhance couplings between nuclei via coherent stimulation



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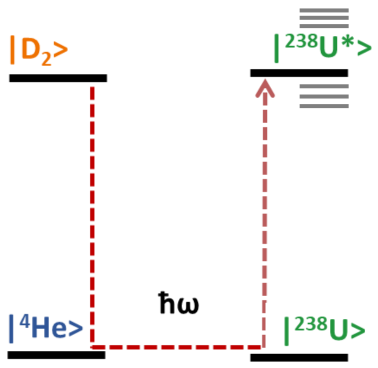

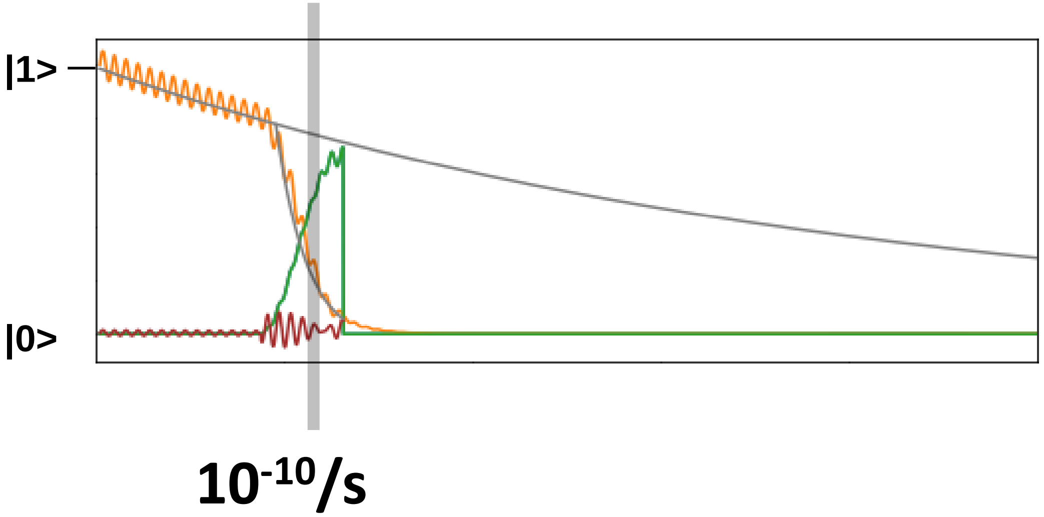

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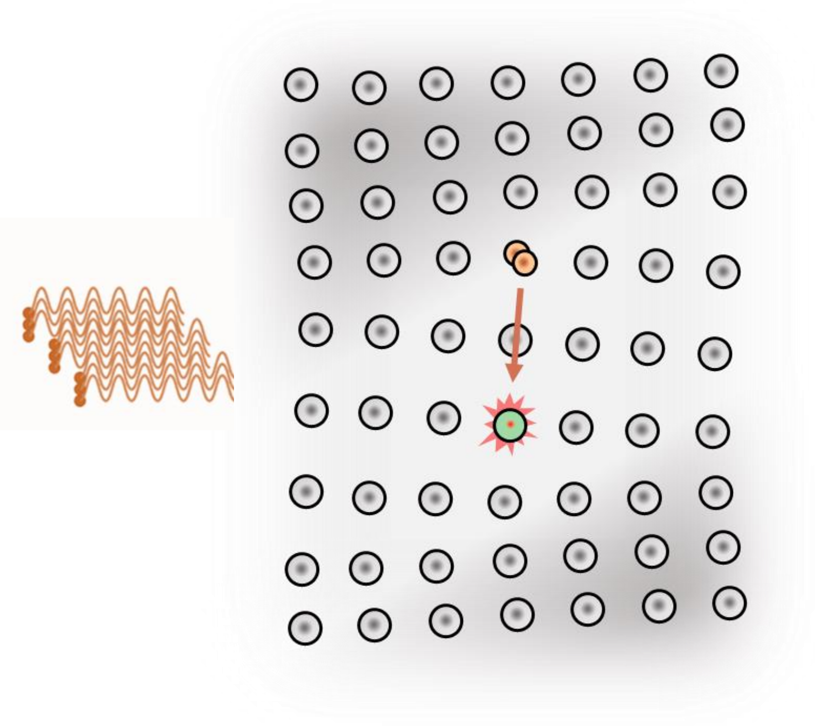
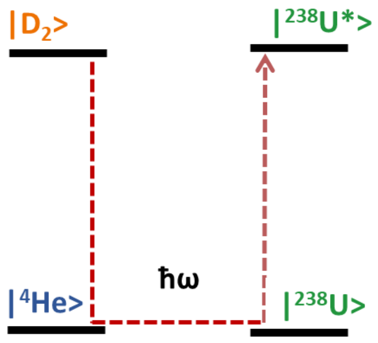
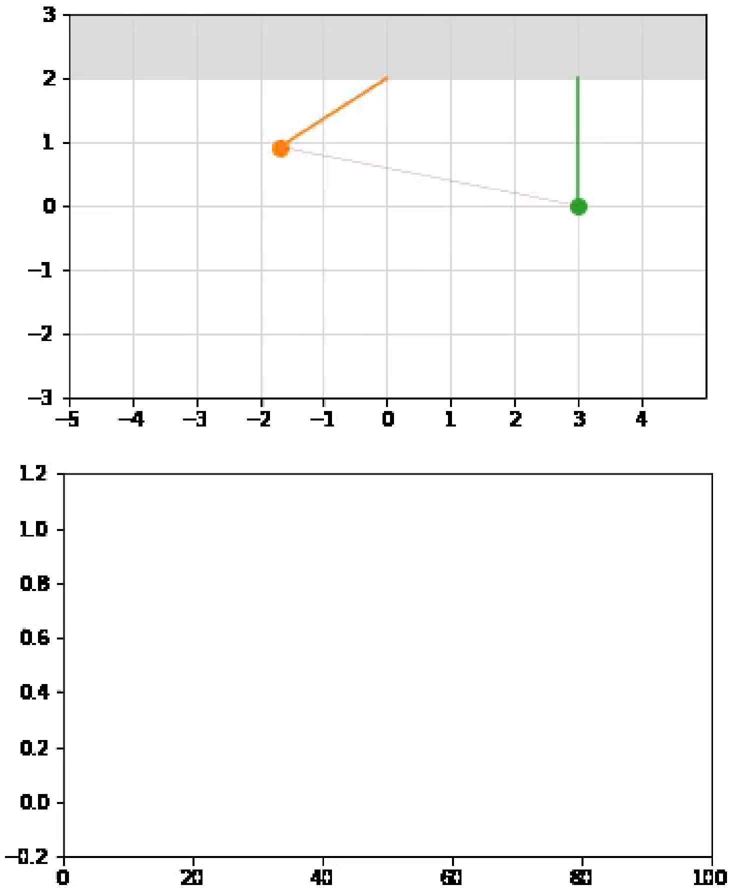
Combining screening and transition rate enhancement

Building intuition through mechanical analogs





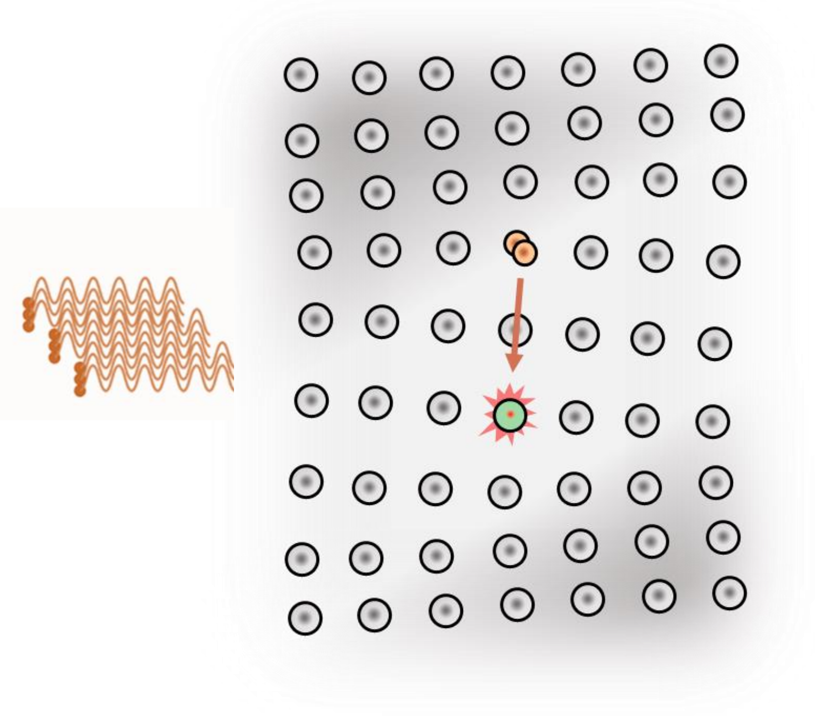


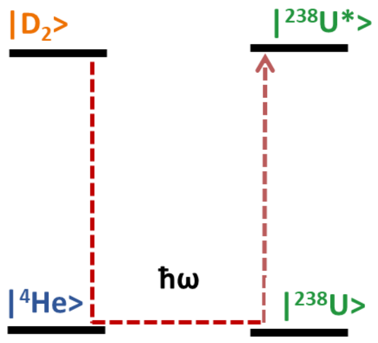
kinetic energy (classical) ≙ state occupation probability (quantum)

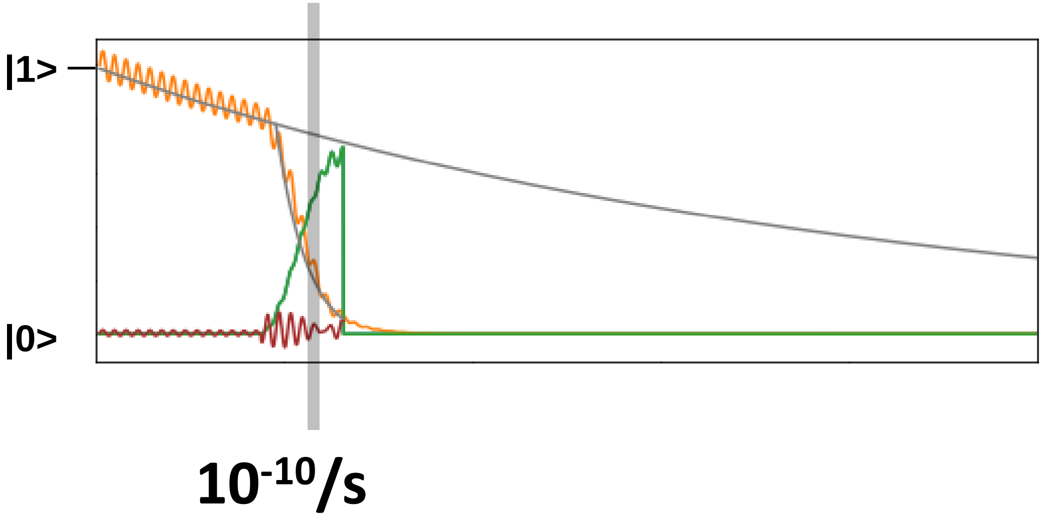
Briggs, J. S., & Eisfeld, A. (2012). Coherent quantum states from classical oscillator amplitudes. Physical Review A, 85(5), 052111.

Combining screening and transition rate enhancement

Couplings between resonant nuclei accelerate transitions







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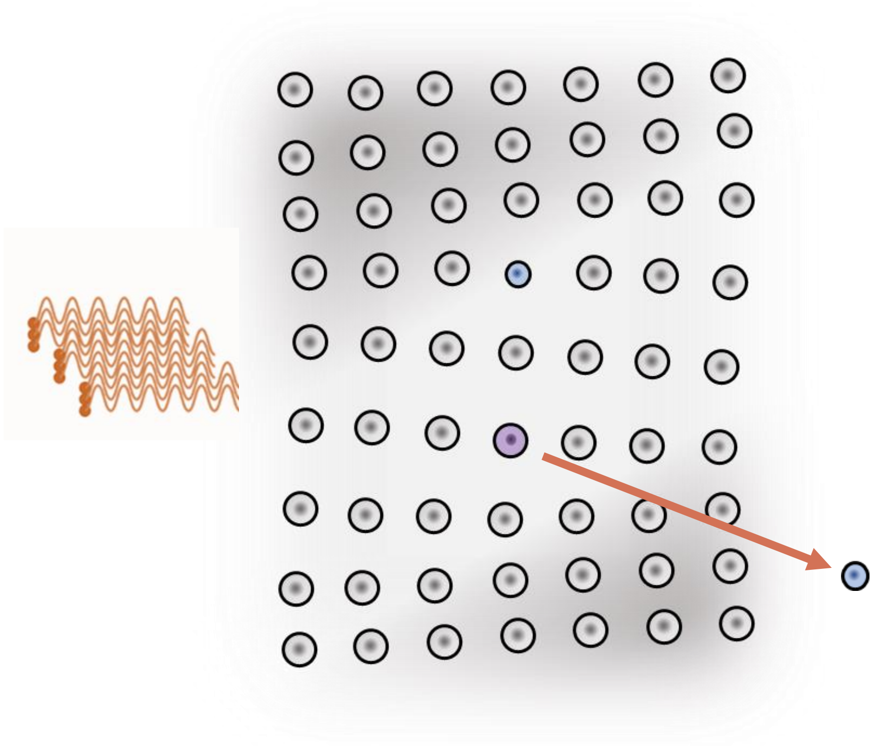
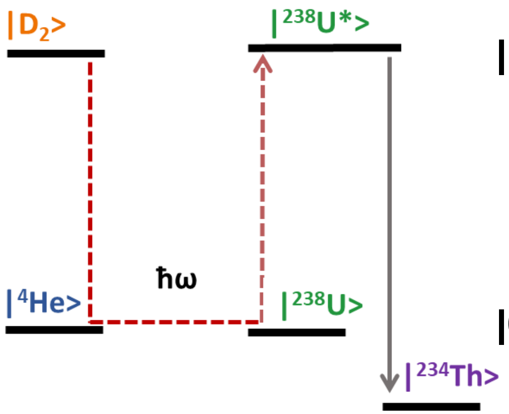
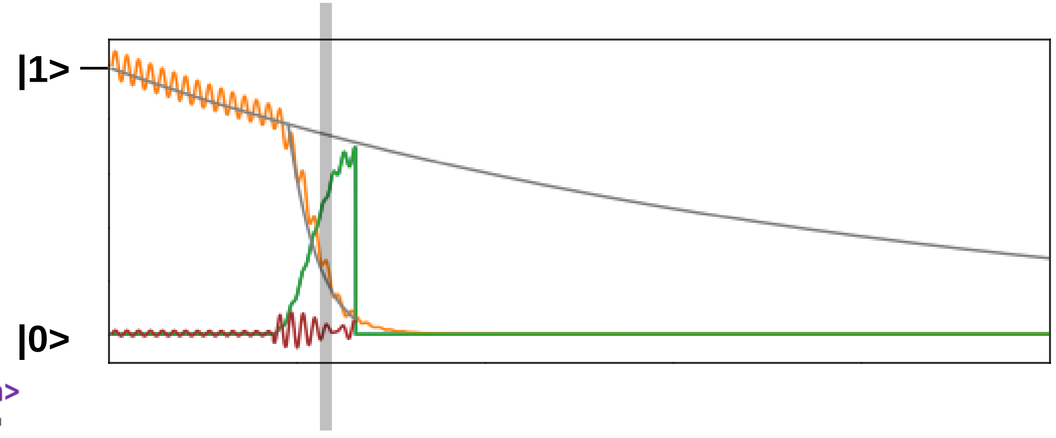
Combining screening and transition rate enhancement

Receiver nucleus disintegrates







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Hagelstein, P. L. (2020). Models based on phonon-nuclear coupling. In Cold Fusion (pp. 283–300). Elsevier.
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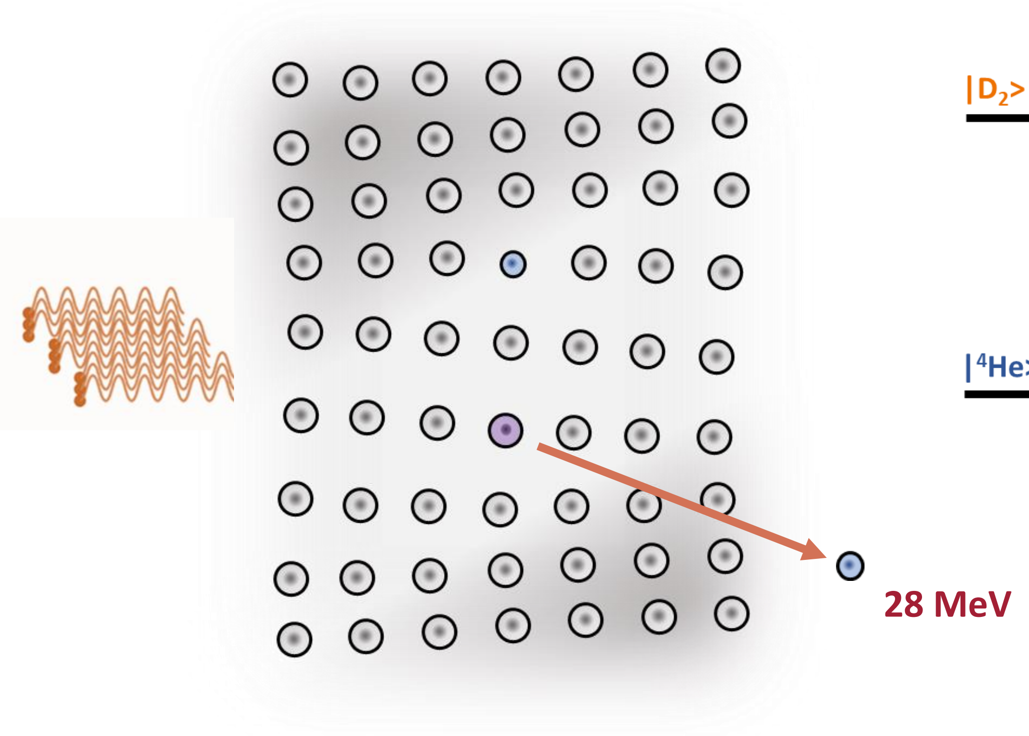
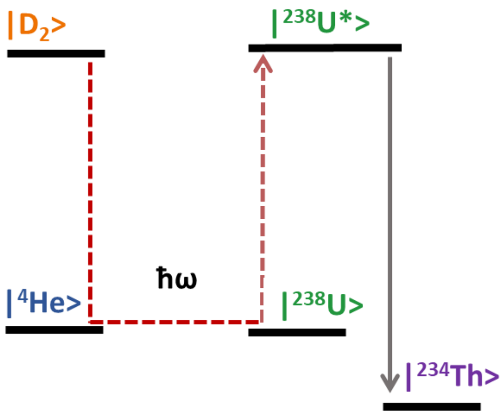
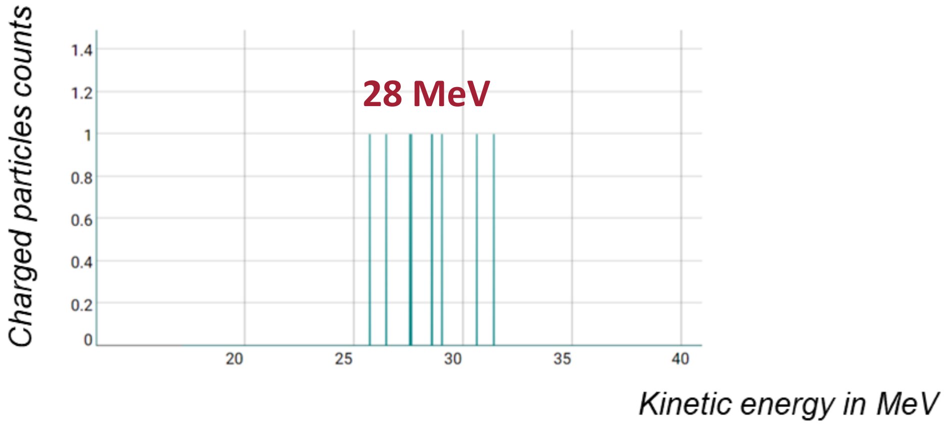
Combining screening and transition rate enhancement

Explanation for anomalies in MIT experiments



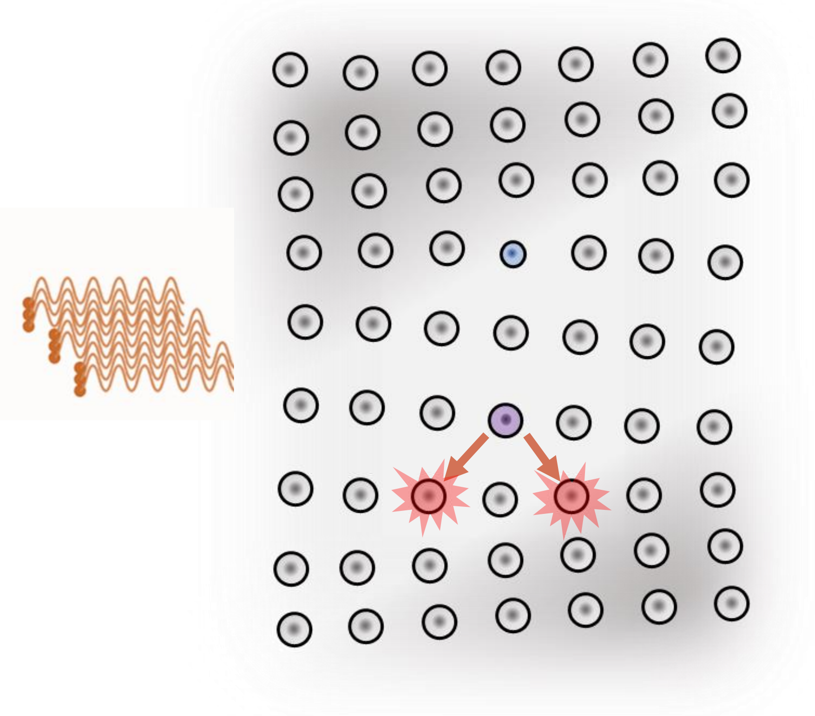


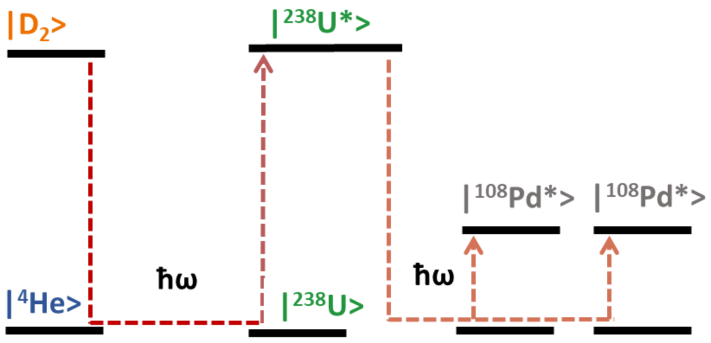


28 MeV charged particle counts from bombarded Ti foil

Combining screening and transition rate enhancement

Alternative secondary and tertiary reactions





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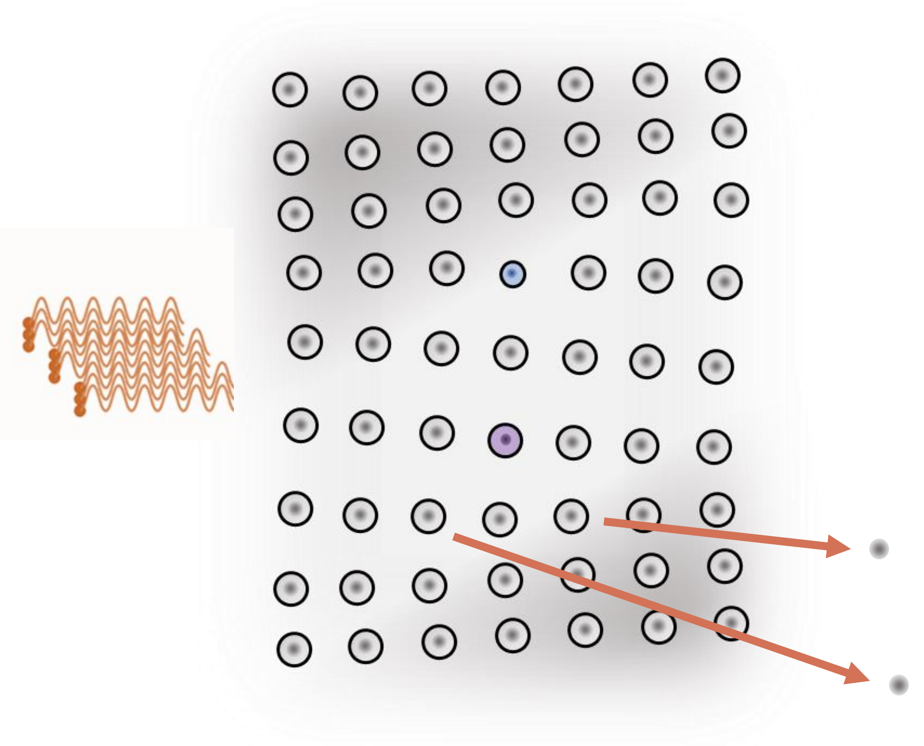
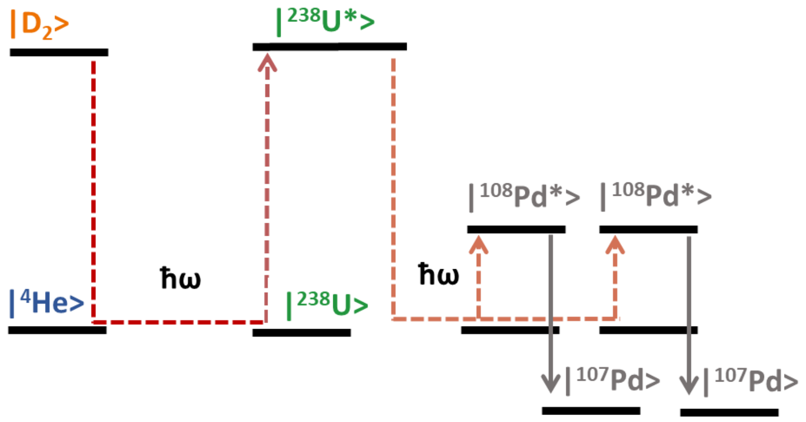
Combining screening and transition rate enhancement

Explanation for anomalous neutron emission





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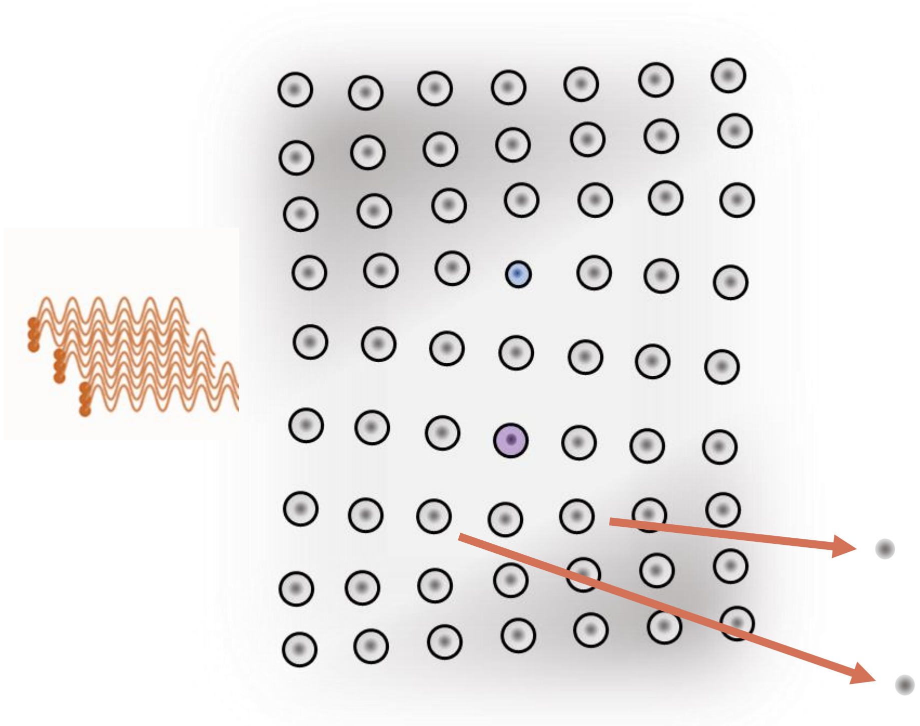
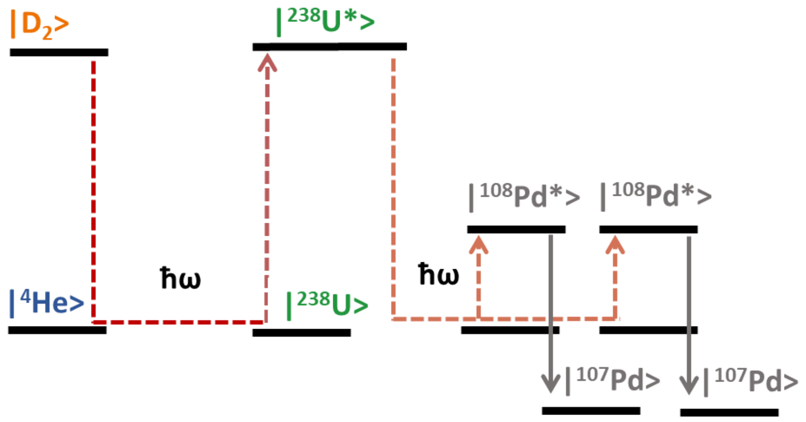
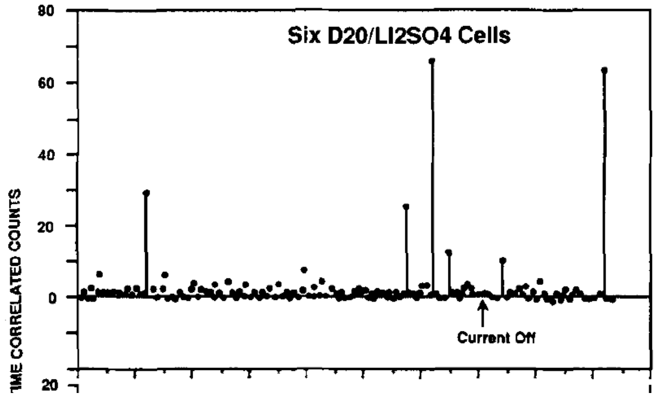
Combining screening and transition rate enhancement

Explanation for variety of experimental outcomes





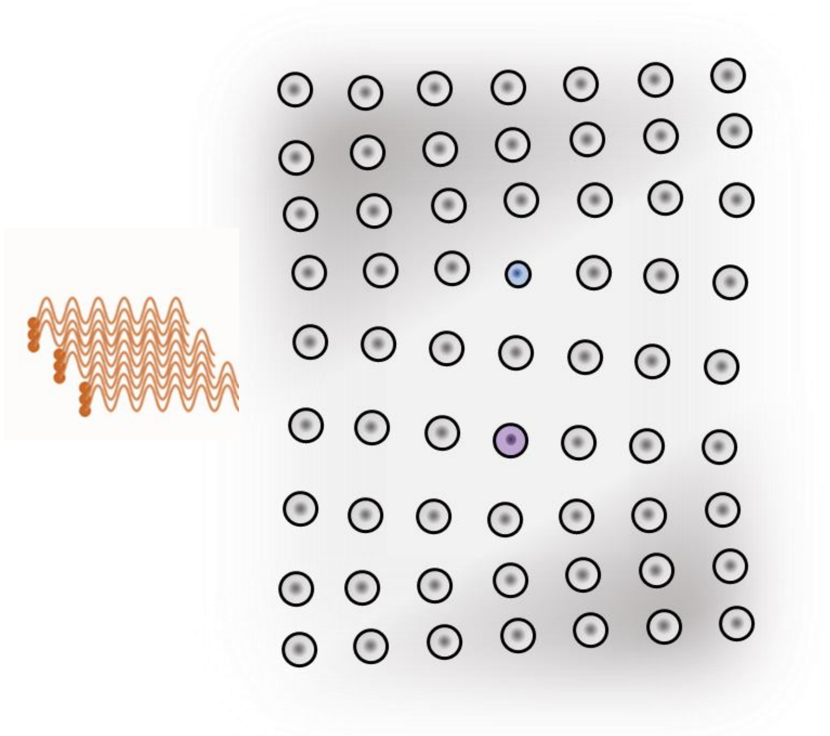


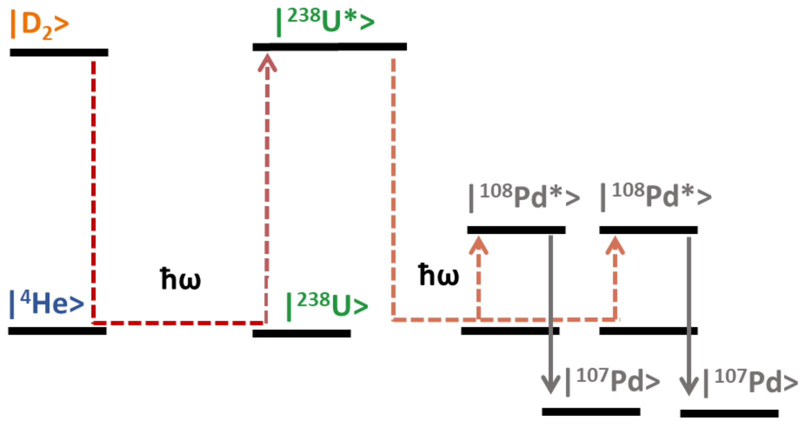
Caution:
This implies that in some configurations you would expect observable energetic particles -- and in others you would not!

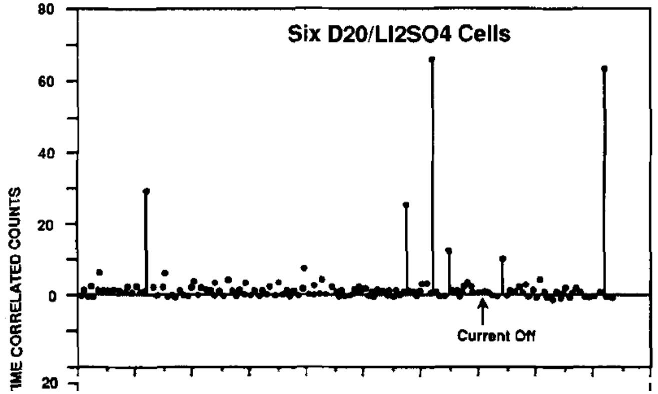
Jones, S. E., Palmer, E. P., Czirr, J. B., Decker, D. L., Jensen, G. L., Thorne, J. M., Taylor, S. F., & Rafelski, J. (1990). Anomalous nuclear reactions in condensed matter: Recent results and open questions. Journal of Fusion Energy, 9(2), 199–208.

Combining screening and transition rate enhancement

Explanation for variety of experimental outcomes







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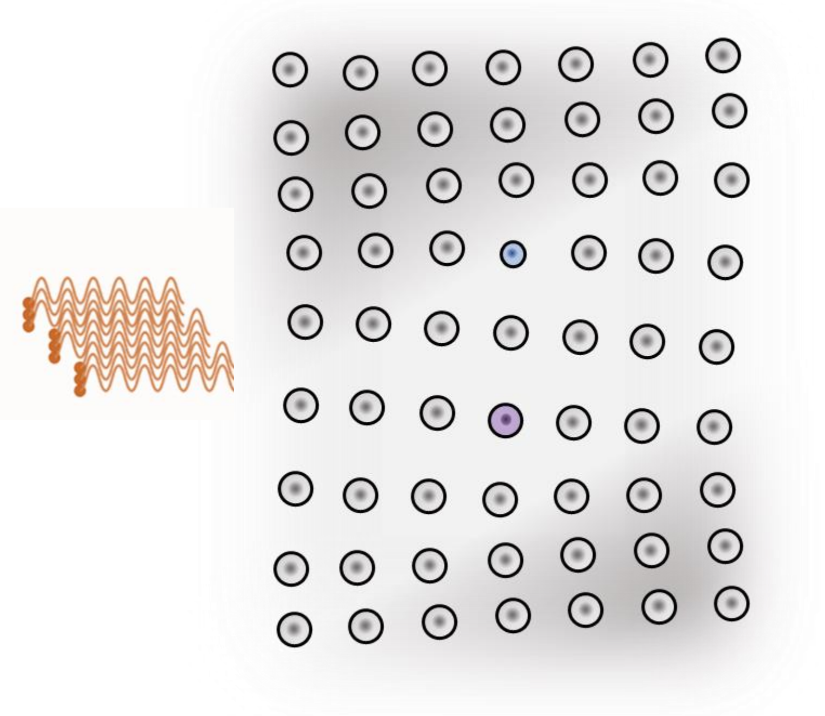
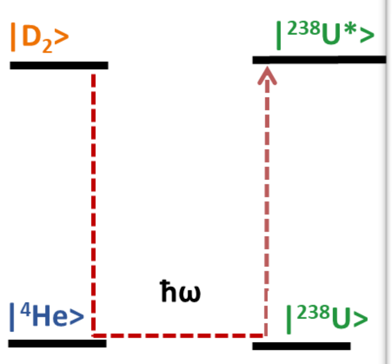
Combining screening and transition

Explanation for variety of experimenta





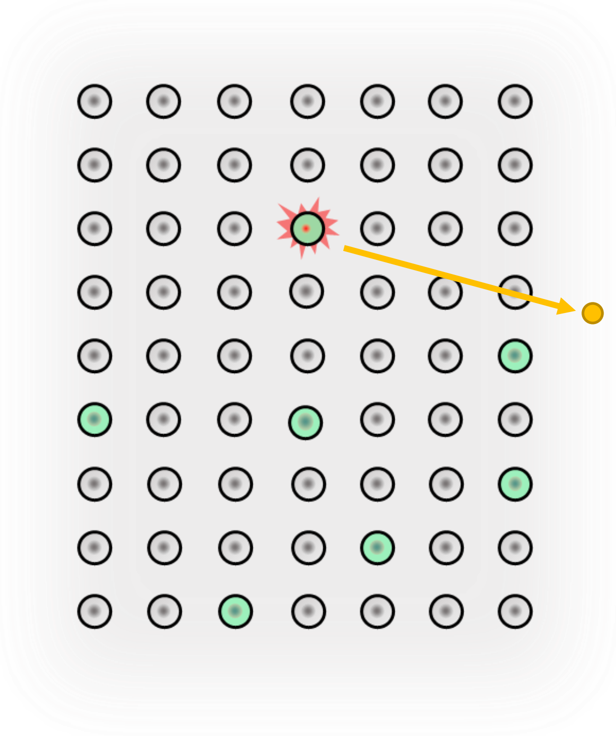
Bottom-up experiment

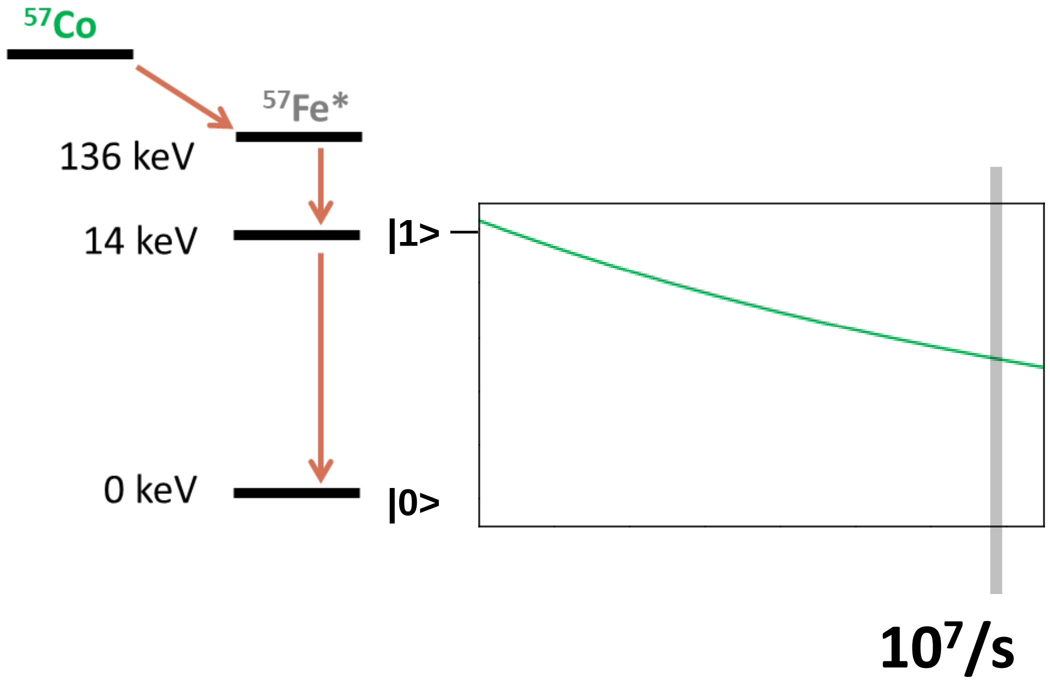
HEAT	None expected
ENERGETIC PARTICLES	28 MeV per reaction site (D2 and U-238 pair)
LATTICE COMPOSITION	PdD with 0.0001% U-238 dopants
+ CHANGES	DD → He-4; U-238 → Th-234
LATTICE MORPHOLOGY	PdD with >10% VacH clusters
+ CHANGES	damage from charged particles
LATTICE DYNAMICS	10 THz phonons
+ CHANGES	Possibility of downconversion to phonon modes

Hagelstein, P. L. (2020). Models based on phonon-nuclear coupling. In Cold Fusion (pp. 283
Hagelstein, P. L. (2018). Phonon-mediated Nuclear Excitation Transfer. J. Cond. Mat. Nucl.

Connecting with established literature

Accelerating Fe-57 nuclear emission





Hagelstein, P. L. (2020). Models based on phonon-nuclear coupling. In Cold Fusion (pp. 283–300). Elsevier.
Metzler, F. (2019). Experiments to Investigate Phonon-Nuclear Interactions [Thesis]. Massachusetts Institute of Technology.

Connecting with established literature

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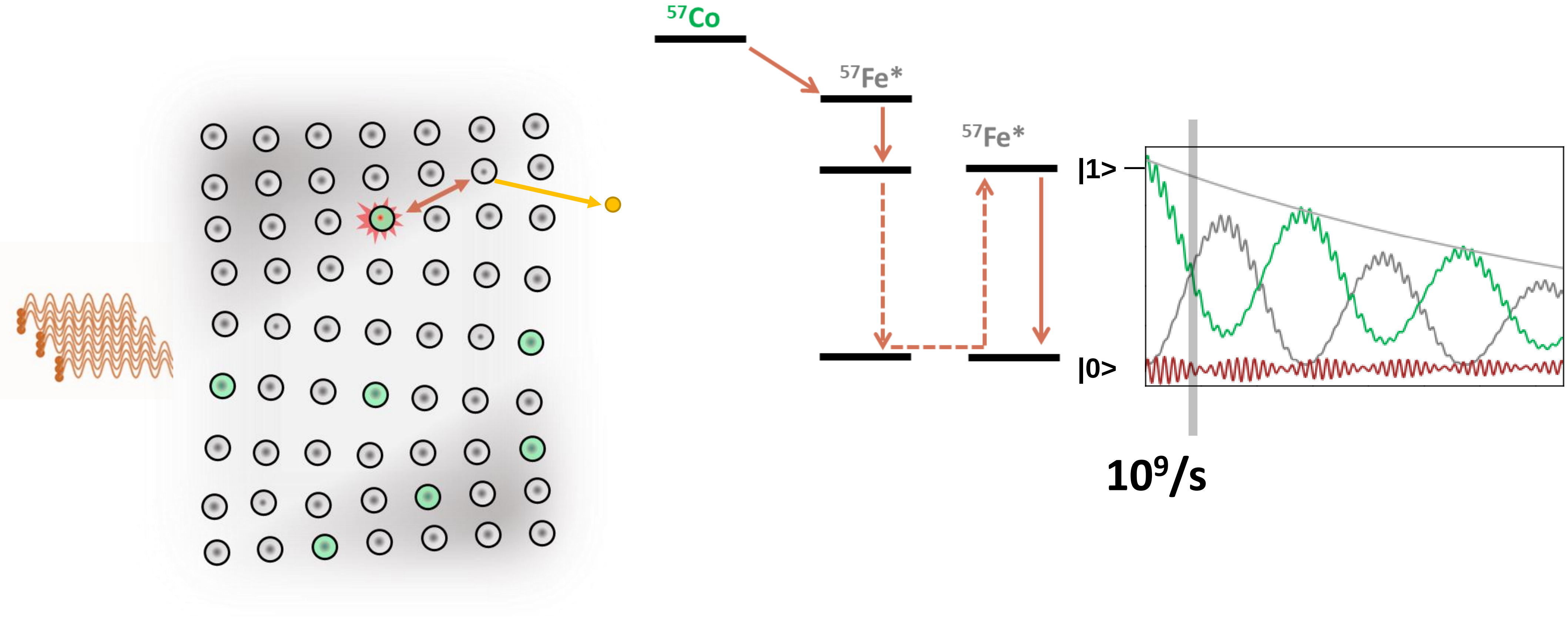

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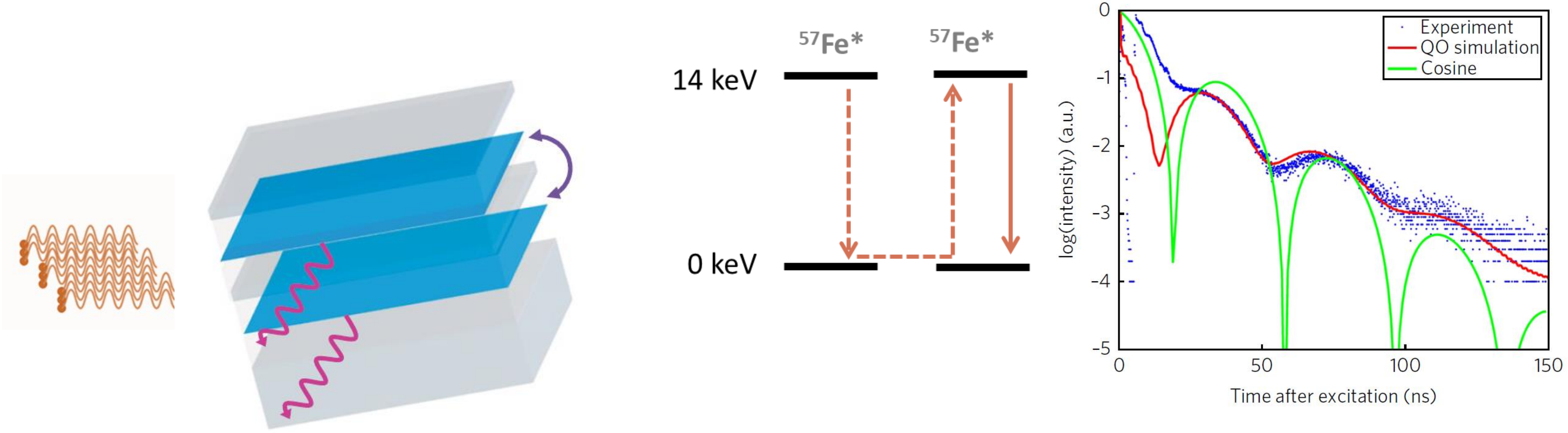
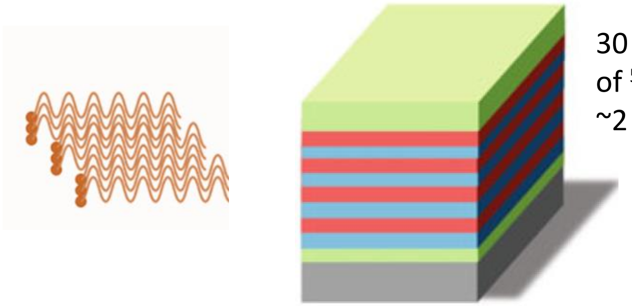


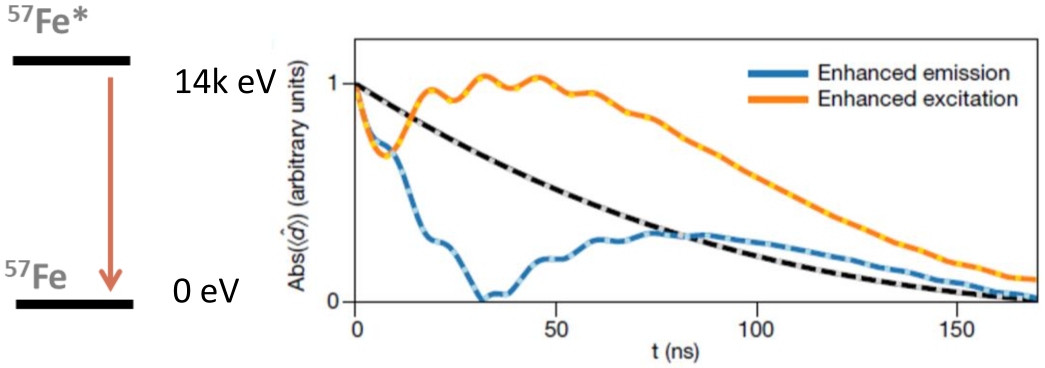
Haber, J., Kong, X., Strohm, C., Willing, S., Gollwitzer, J., Bocklage, L., Rüffer, R., Pálffy, A., & Röhlsberger, R. (2017). Rabi oscillations of X-ray radiation between two nuclear ensembles. Nature Photonics, 11(11), 720–725. https://doi.org/10.1038/s41566-017-0013-3

Connecting with established literature

Accelerating Fe-57 nuclear emission



30 bilayers
of $^{57}Fe/^{56}Fe$
~2 nm each



Accelerated (blue) and delayed (orange) decay of excited states in Fe-57 nuclei due to strong couplings to resonant neighboring nuclei.

Heeg, K. P., Kaldun, A., Strohm, C., Ott, C., Subramanian, R., Lentrodt, D., Haber, J., Wille, H.-C., Goerttler, S., Rüffer, R., Keitel, C. H., Röhlsberger, R., Pfeifer, T., & Evers, J. (2021). Coherent X-ray–optical control of nuclear excitons. Nature, 590(7846), 401–404.

Conclusions

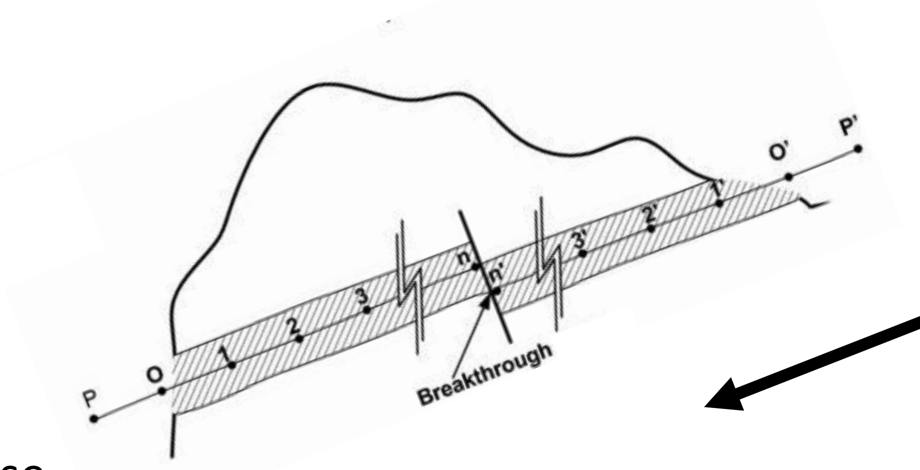
Key points

- A reference experiment needs to be both reproducible and unambiguous.
- Historically, emphasis has been on characterization modes that leave too much room for alternative explanations (heat) → *high ambiguity.*
- Going forward, prioritize characterization modes that are intrinsically more unambiguous (e.g. Raman spectroscopy for lattice vibrations).
- There are still too many uncharacterized/uncontrolled variables in any of the major experiments → *low reproducibility.*

Conclusions

Key points (2)

- In future research, employ a two-pronged approach:



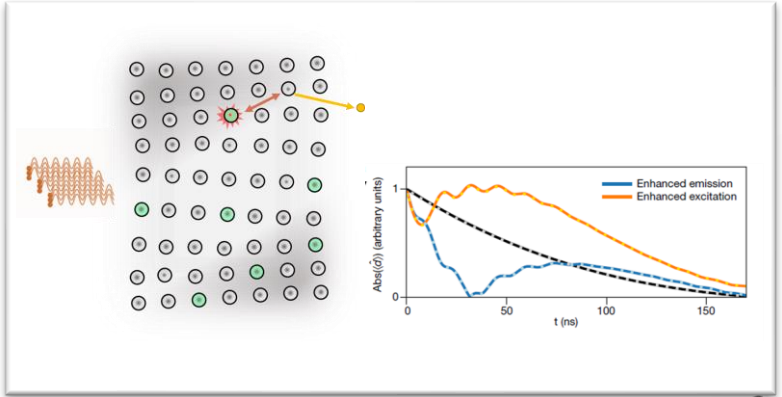
Top-down:
comprehensive characterization of a small number of legacy experiments (focus!)

Bottom-up:
simple experiments with precise specifications based on hypotheses about mechanism; connect with adjacent literatures on accelerated state transitions

Conclusions

Key points (2)

- In future research, employ a two-pronged approach:



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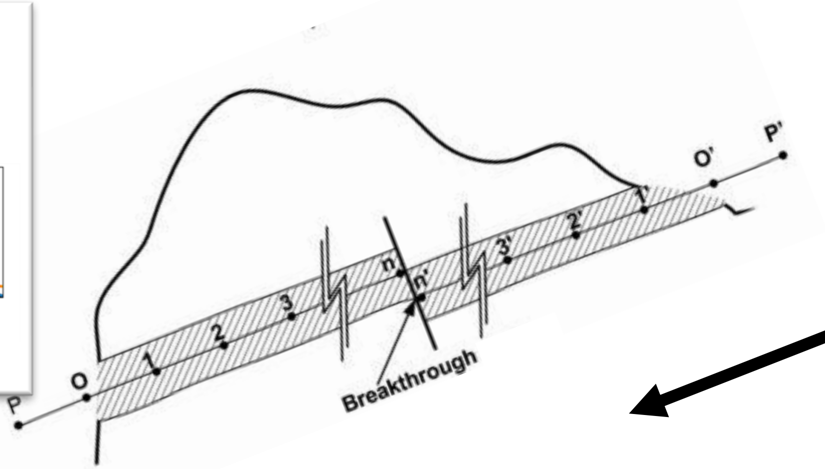

Top-down:
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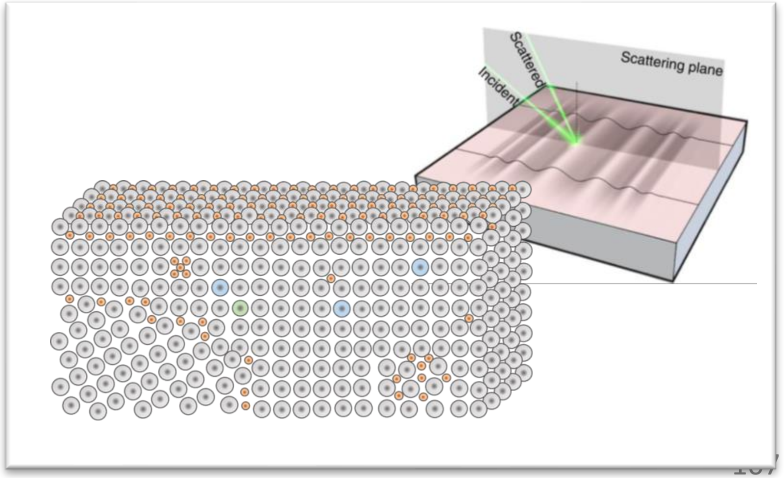
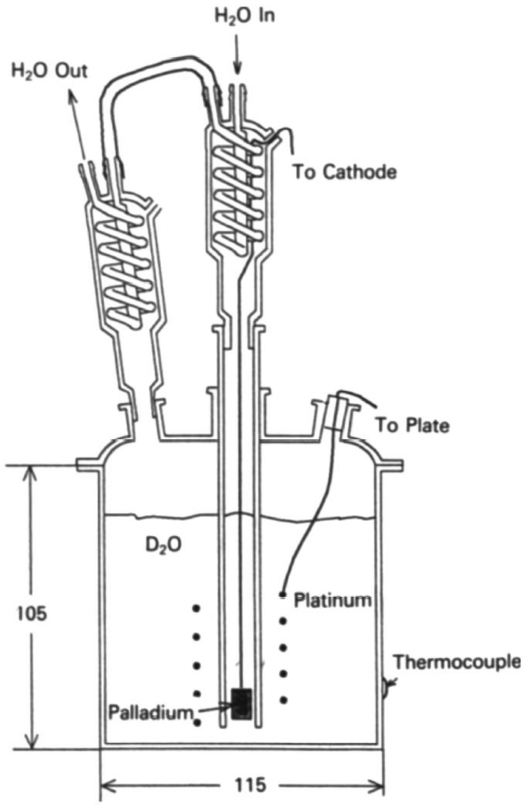
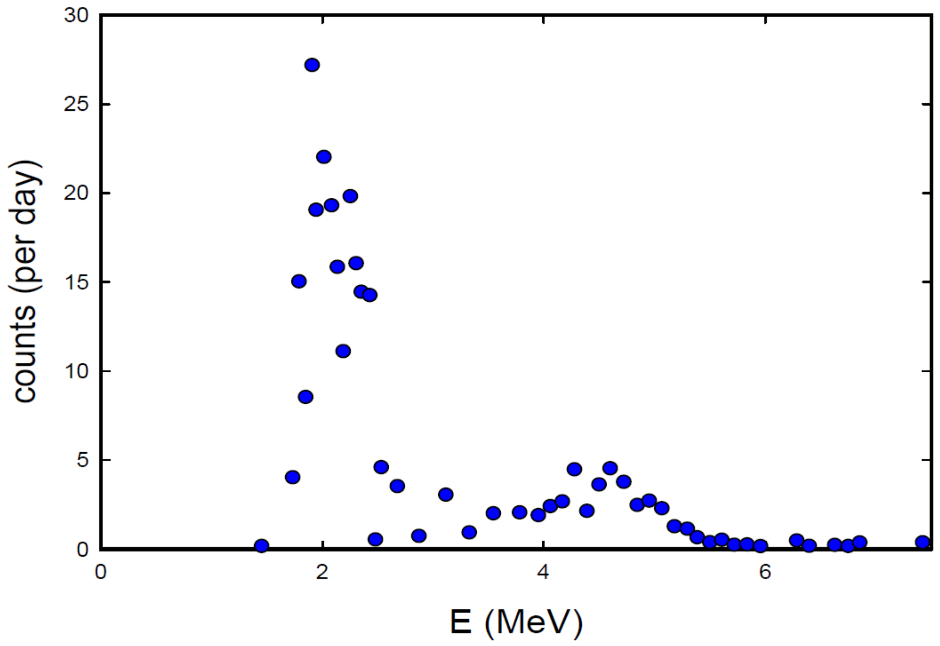


Example: Neutron emission from loaded Pd foil (2)



Experimental setup:
electrochemical cell above neutron spectrometer

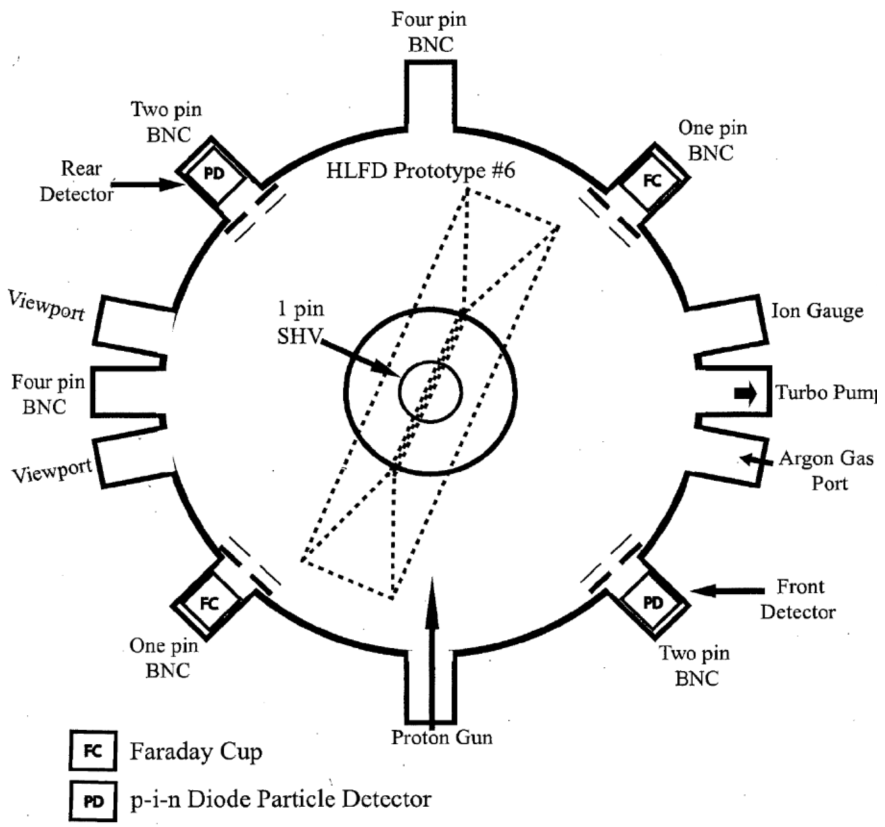


Neutron spectrum centers around 2 and 5 MeV.

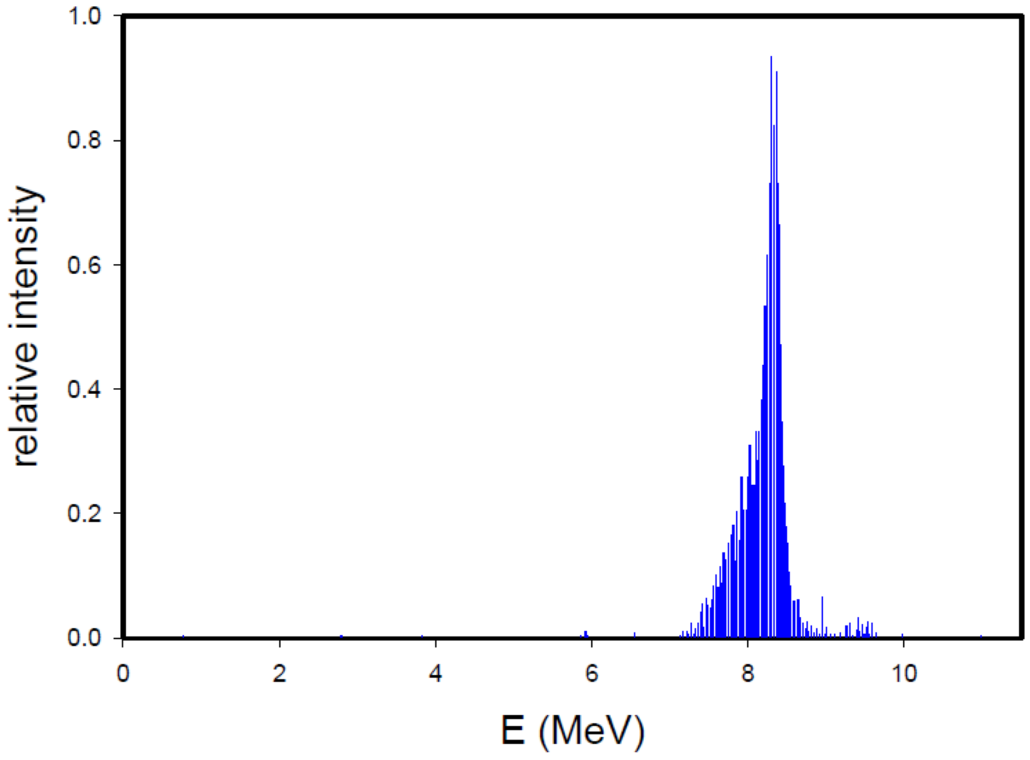
Takahashi, A., Iida, T., Maekawa, F., Sugimoto, H., & Yoshida, S. (1991). Windows of cold nuclear fusion and pulsed electrolysis experiments. Fusion Technology, 19(2), 380–390.
Takahashi, A., Takeuchi, T., Iida, T., & Watanabe, M. (1990). Emission of 2.45 MeV and higher energy neutrons from D2O-Pd cell under biased-pulse electrolysis. Journal of Nuclear Science and Technology, 27(7), 663–666.

Characterization mode: energetic particles

Example: Charged particle emission from loaded Li foil



Experimental setup: Vacuum chamber with low-energy deuteron beam on foil target



9 MeV alpha peak from bombarded Li foil

Lipinski, S. A., & Lipinski, H. M. (2015). Hydrogen-lithium fusion device (World Intellectual Property Organization Patent No. WO2014189799A9).

CANDIDATE REACTIONS	D+D→?, D+P→?, P+P→?	D+D→?, D+P→?, P+P→?	D+D → He-4 driving neutron emission (5 MeV) from Pd*	D+D → He-4 driving alpha emission (21 MeV) from Pd*	D+D → He-4 driving alpha emission (28 MeV) from U*	D+D → He-4	D+D → He-4 driving Pd fission	D+D → He-4 driving Pd fission	D+D→?, D+P→?, P+P→?	D+D→?, D+P→?, P+P→?	D+D→?, D+P→?, P+P→?

+ CHANGES

+ CHANGES